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Evidence of a decreasing trend in rainfall at northern part of the municipality of Ensenada, Baja California, México from 1978 to 2011

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Resumen

En este estudio de caso, se demuestra en términos estadísticos que desde 1978 hasta el 2011, el nivel de precipitación total disminuyó significativamente en la parte del municipio de Ensenada que se encuentra entre las latitudes 31° N y 33° N, en el estado de Baja California, México. Junto con los cambios a largo plazo observados en la precipitación total anual de esta región, mediante un análisis de tendencias por separado para cada mes del año, observamos una descomposición práctica de los cambios sostenidos registrados durante este período de tiempo. Un nivel de significancia del cinco por ciento fue aplicado, tanto en la prueba de Mann-Kendall como en el *t*-test con el fin de obtener estimaciones cualitativas y cuantitativas de las tendencias observadas.

Se muestra que la parte norte de Ensenada ha ido perdiendo las precipitaciones en el transcurso de las últimas tres décadas y media. esto ha ocurrido principalmente en los meses de Marzo y Septiembre. Estos resultados pueden favorecer las decisiones y las acciones oportunas en relación con la administración del agua de esta importante zona agrícola.

Palabras clave: prueba de Mann-Kendall, *t*-test, análisis de tendencias, cambio climático.

Abstract

In this case study, it is proved in statistical terms that from 1978 to 2011 the level of total rainfall decreased significantly in the portion of the municipality of Ensenada that lies between latitudes 31°N and 33°N, in Mexico's state of Baja California. Along with the observed long-term changes in this region's yearly total rainfall, a separate trend analysis for each month of the year offers a practical decomposition of the sustained changes recorded during this period of time. With a five percent significance level, both the Mann-Kendall test and the *t*-test are applied in order to obtain qualitative and quantitative estimates of the trends observed.

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It is shown that the northern part of Ensenada has been losing rainfall in the course of the last three and a half decades and that this has occurred mainly in the months of March and September. These results can favor timely decisions and actions regarding the water management of this important agricultural area.

Key words: Mann-Kendall test, *t*-test, trend analysis, climate change.

Introduction

Climate change affects Mexico in many ways. One of the most serious transformations observed is a sustained decrease in rainfall that has occurred over the last few decades in some portions of the country, like the state of Baja California that appears shaded in white on Figure 1.

This paper is a case study, in the line of research presented by Méndez-González et al. (2008) and Mondal et al. (2012). Within the state of Baja California, it focuses on the northern part of the municipality of Ensenada, composed of the port of Ensenada and a thriving agricultural region. In particular, this area contains Guadalupe Valley, where wine production has prospered remarkably in the last few decades, generating considerable economic growth. The precise surface is illustrated by Figures 2a and 2b. It counts with sufficient data recorded by twenty four meteorological stations, making it possible to provide local decision makers with substantial statistical evidence of a significant decline in total rainfall.

The results presented below are intended to foster sustainable use and conservation of water. They also aim to promote social awareness and understanding of proven climate change. Besides, the methodology offered here applies equally well to analyze the long-term evolution of other essential variables, such as mean temperature, dam storage and net aquifer recharges. A regional approach to the subject is also recommended, with the advantages and disadvantages of considering a larger area that might stretch from the Mexican state of Baja California Sur to the North American state of California (Figures 1 and 2a).

Above all, the purpose of this research is to contribute conclusive scientific evidence of actual (not future) climate change, showing how revealing a local analysis can be.

Materials and Methods

a) Input

Ensenada is one of the largest municipalities (or counties) in Latin America. The climate changes it faces vary slightly from north to south, hence the present study is limited to the surface of Ensenada that lies at a latitude equal or greater than 31°N.

This area has many weather stations recorded by Mexico's National Meteorological Service (Servicio Meteorológico Nacional, SMN), twenty four of which are used here as they provide at least twenty recent years of monthly data on the region's total rainfall from January 1978 to February 2011 (Table 1). The corresponding data is not included here because it consists of more than nine thousand values.

The arithmetic mean of the data received generates

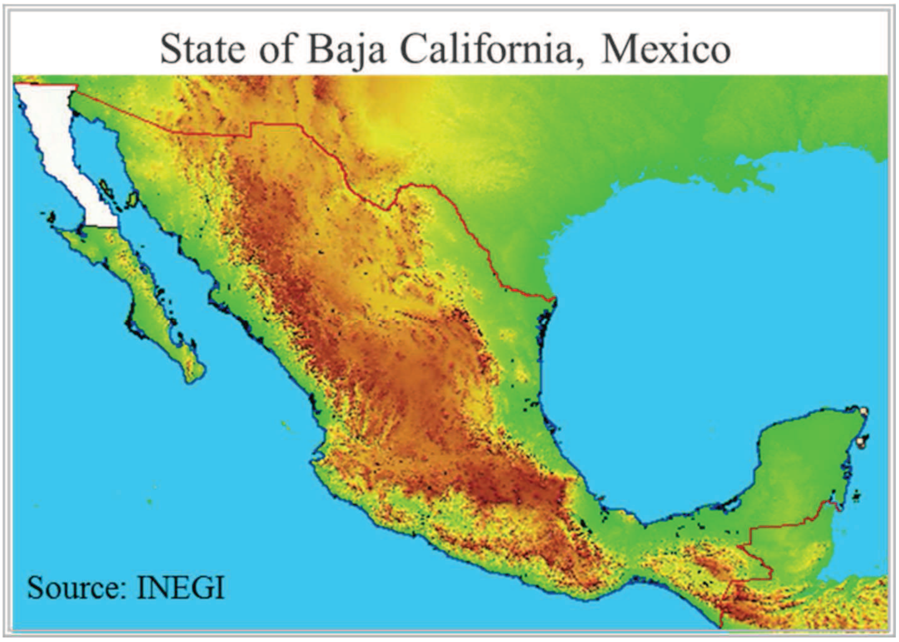


Figure 1: State of Baja California, Mexico

Table 1: Selected meteorological stations

24 Selected meteorological stations Northern Ensenada, Baja California Key and geographical coordinates at 31°N and 32°N of latitude								
Key	Name	Longitude West[1/]			Latitude North[1/]			Altitude[2/]
		D	M	S	D	M	S	MASL
2001	Agua Caliente	116	27	15		6	27	400
2004	Ignacio Zaragoza -Belén-	116	29	8		11	43	540
2005	Boquilla Santa Rosa de la Misión	116	46	37		1	18	250
2036	Olivares Mexicanos	116	40	51	32	2	57	340
2077	La Misión	116	48	40		6	7	20
2156	El Florido	116	49	16		28	20	250
2164	Ejido El Porvenir	115	51	8		6	23	330
2025	Ensenada (Obs)	116	36	21		51	28	21
2045	San Carlos	116	27	49		47	7	164
2056	San Vicente	116	14	52		19	45	110
2065	Santo Tomás	116	24	22		47	31	180
2072	Presa Emilio López Zamora	115	35	50		53	45	43
2079	El Alamar	116	12	14		50	8	710
2088	Ejido Héroes de la Independencia	115	56	15		36	37	1,000
2091	Ejido Ignacio López Rayón	116	15	52		17	16	170
2092	Ejido San Matías	115	32	37	31	19	53	968
2096	La Calentura	116	2	13		16	13	210
2104	El Ciprés	116	35	17		47	25	8
2106	Maneadero	116	34	22		41	44	50
2108	Punta Banda	116	39	58		42	50	15
2118	Valle de San Rafael	116	14	3		55	8	721
2120	Ejido México	116	12	22		4	20	75
2146	Colonia San Pedro Mártir	115	12	15		2	15	416
2153	Ejido Uruapan	116	27	18		37	7	195

NOTE [1/] Units used are D=degrees M=minutes S=seconds

[2/] Unit used is MASL=meters above sea level

Source: SMN

Table 2: Results of trend analysis 1978-2011

Significant trends in monthly and yearly total rainfall Northern Ensenada, Baja California 1978-01 to 2011-02								
	MANN-KENDALL TEST			95% CONFIDENCE INTERVAL				
MONTH	Mann-Kendall statistic	1-*p*	Long term trend	*r*	1-*p*	Lower bound	Rate or slope	Upper bound
Unit	S	Percentage	Conclusion	Percentage		Millimeters per decade		
January	-96	92.95	None detected					
February	37	70.32	None detected					
March	-172	99.60	DECREASING	46.23	99.32	-28.93	-16.99	-5.05
April	-6	53.09	None detected					
May	19	60.99	None detected					
June	104	94.61	None detected					
July	-60	81.97	None detected					
August	-39	72.20	None detected					
September	-113	95.87	DECREASING	35.27	94.84	-2.97[2/]	-1.49	0.00[2/]
October	-88	91.12	None detected					
November	-88	91.12	None detected					
December	-14	57.98	None detected					
Year[1/]	-128	97.55	DECREASING	39.90	97.67	-97.54	-52.60	-7.65

NOTE [1/] Full year with information about its 12 months [2/] Approximate value

Calculated with public data from SMN

thirteen time series describing total rainfall in northern Ensenada, measured in millimeters: one for each month of the year (Mondal et al*.*, 2012) and one for the corresponding yearly total.

Note that the arithmetic mean calculated in the step above is not the only choice: the median value can take its place (Khambhammettu, 2005). It is also important to add that the raw input can occasionally be impoverished or biased by missing data.

b) Trend analysis

The thirteen time series obtained above are examined separately. A double test for monotonic trend is applied to each one, following the methodology of parametric and non-parametric Statistical Inference in order to detect and measure any long-term trend showing a 5% significance level (Helsel et al., 2002).

Basically, the two techniques described below are applied: the Mann-Kendall test and the *t*-test. When both reach the same conclusion, the corresponding result is accepted and documented. Sometimes both methods share the same conclusion as long as a level of significance slightly greater than 5% is accepted for the *t*-test, which is considered adequate. In some instances, the outcome of both tests is contradictory, but the corresponding quality control and residual analysis generally shed enough light to solve the problem in a satisfactory manner.

When the null hypothesis is not rejected, it might be that the time series has no monotonic trend, or that the evidence doesn't meet the 5% significance standard.

c) Mann-Kendall test

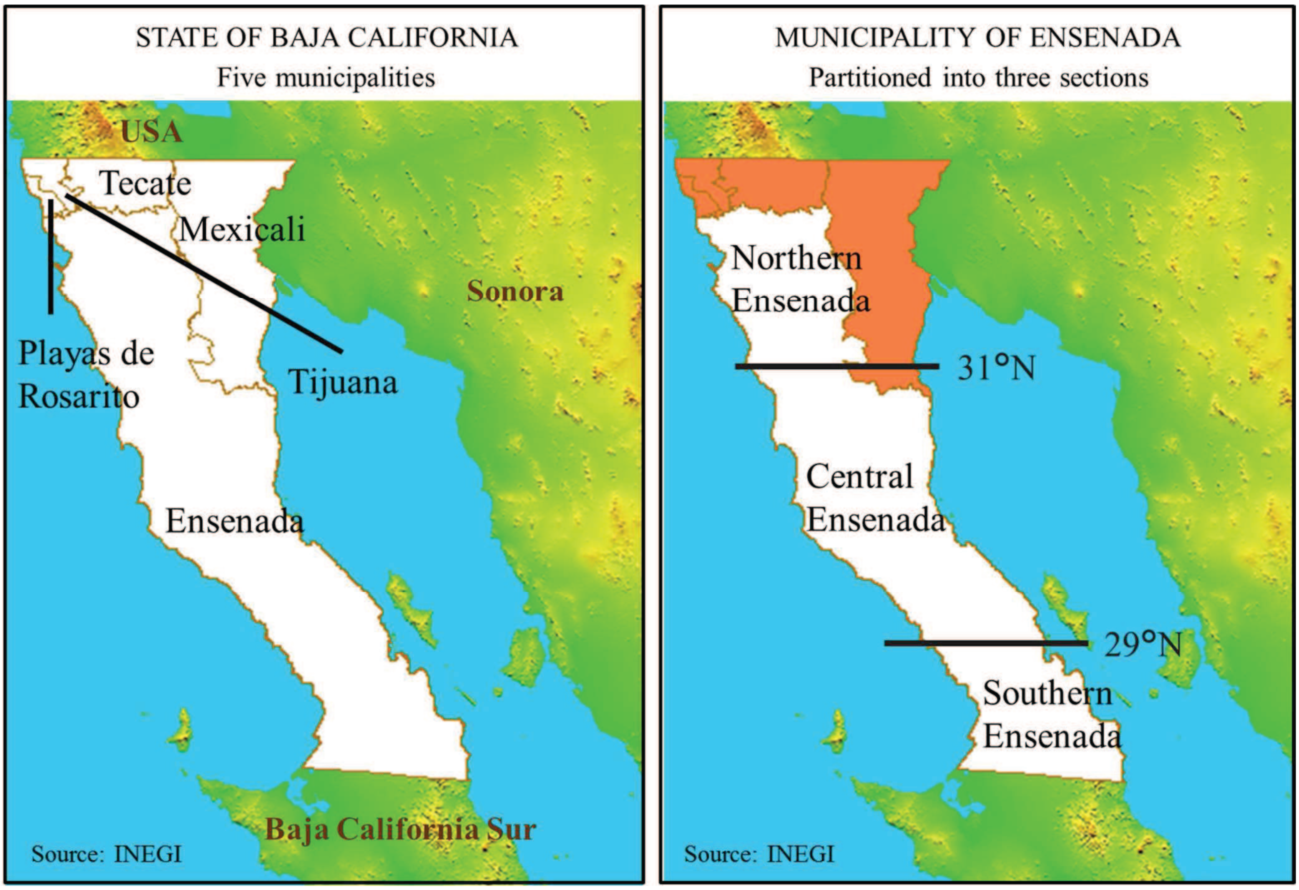
The Mann-Kendall test is a non-parametric hypothesis test. It applies to time series that are free of significant autocorrelations in order to determine whether they present a monotonic trend, as it chooses between the following null and alternative hypotheses.

H_0 *: the time series is made up of values that are the realization of identically distributed random variables*

H_1 *: the values present a monotonic increasing or decreasing trend, not necessarily linear.*

This is a robust test that depends only on the relative magnitude of the given data, hence it is the most frequently used in monotonic trend analyses of hydrologic time series (Hossain et al., 2013; Méndez-González et al., 2008). It is applied to the raw input by means of a programmed Excel file that processes the thirteen series being analyzed in a single run.

In short, for a given time series made up of ten or more real values $x_1, x_2, \ldots, x_n$ the Mann-Kendall statistic S is the sum of all possible terms $sign(x_k - x_j)$ in which $1 \leq j < k \leq n$, where $sign(x_k - x_j)$ takes the value 1, 0 or -1 if x_k is greater,



Figures 2a and 2b: Northern Ensenada in Baja California

equal or smaller than x_j, respectively. Thus the absolute value of S is greater when the time series contains mostly increasing (S positive) or decreasing values (S negative).

If the given time series contains no repeated values, the *variance of S* is given by

$$Var(S) = [\, n(n-1)(2n+5)\,] / 18$$

Otherwise, the series has a total of g distinct repeated values that are grouped into sets $C_1, C_2, \ldots, C_g$ of cardinality $t_1, t_2, \ldots, t_g$, respectively. In this case, the *variance of S* is given by

$$Var(S) = (1/18) * [\, n(n-1)(2n+5) - S\, t_p(t_p-1)(2t_p+5)\,]$$

where the indicated sum runs from $p = 1$ to $p = g$.

Finally, the test statistic Z is defined as $(S-1)/[Var(S)]^{1/2}$, 0 or $(S+1)/[Var(S)]^{1/2}$ if the value of S is positive, zero or negative, respectively.

As the value of n increases, the distribution of the random variable Z asymptotically approaches that of a standard normal distribution, i.e. one of zero mean and unit variance.

Therefore, with a significance level of 5%, the time series is said to present an increasing (decreasing) trend when S is positive (negative) and the absolute value of Z is greater than 1.645, in which case the null hypothesis is rejected.

Note that the Mann-Kendall test in itself is qualitative, as it doesn't estimate the actual rate at which the time series is actually increasing or decreasing.

d) t-test

This method stems from the well-known *linear regression model*, in which an optimal straight line is fitted to the given time series by the least squares method. The one-tailed *t*-test confronts the hypothesis of a zero slope in the optimal straight line against a positive (negative) value of the slope, in which case a rejection of the null hypothesis determines an increasing (decreasing) trend in the data. This test is performed at a 5% significance level and an estimate for the slope's value is generated by the corresponding 95% confidence interval (Chatterjee et al., 2000).

In this way, the *t*-test generates results that are qualitative and quantitative. Its various hypotheses and calculations are not reproduced here, as they can be easily found in textbooks on Statistical Inference.

This method calls for adequate treatment of all atypical and influential values that may be present in the raw time series being analyzed. Different decisions in this respect generate slightly different estimations of the rate of change in the data, which is why this technique is less robust than the Mann-Kendall test. It must also be noted that estimates are also altered when a transformation is applied to the

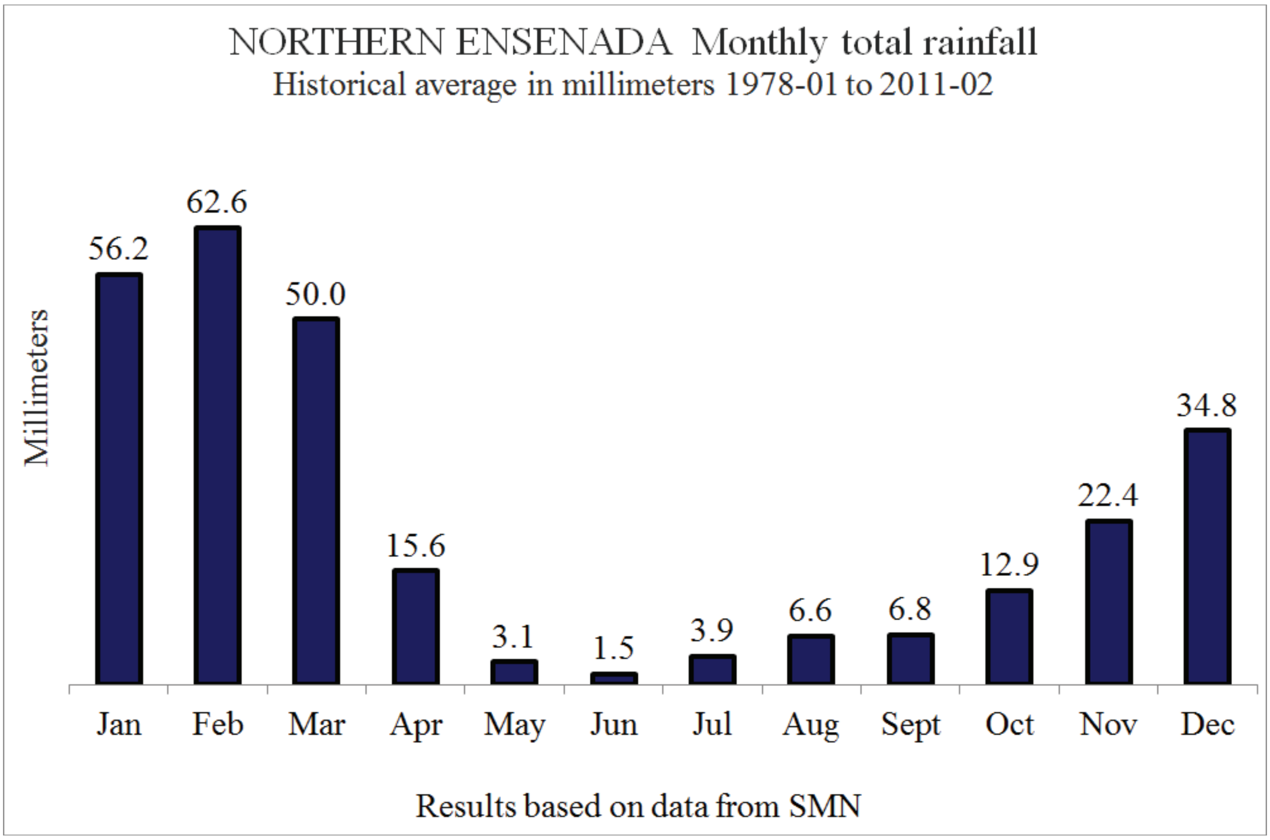


Figure 3: Average total rainfall per month 1978-2011

data in order to ensure that the relationship between time and the given series is linear, or to make the variance of residues constant.

Once more, a programmed Excel file processes the thirteen series jointly, in a single run. For each series considered, another programmed Excel file applies twelve routines simultaneously, so as to provide detailed quality control and a residual analysis.

Finally, the rate of change in total rainfall is presented to the reader in millimeters per decade. This is the preferred unit, as it allows the final values to come as close as possible to human perception of the region's climate change.

e) Average total rainfall

With the purpose of illustrating the area's climate, Figure 3 represents the average monthly total rainfall recorded during 1978-2011 in northern Ensenada. It is important to note that the region's rainy season definitely includes the month of March, whereas September belongs to the dry season.

Results

The evidence found for long-term trend in total rainfall is definitive for the northern part of Ensenada and can be summarized as follows (Table 2).

With a 95% confidence level, the yearly total rainfall of northern Ensenada during 1978-2010 recorded a decreasing long-term trend, at a rate that lies between 7.65 and 97.54 millimeters per decade (Figure 4).

As to the trend analysis relative to each month of the year, March presents a significant decrease in total rainfall at a rate between 5.16 and 28.82 millimeters per decade (Figure 5). With this change, the amount of water that falls to the area's surface during the rainy season (and during the entire year) has diminished considerably in the last decades. The relatively dry month of September records a decline in total rainfall at a rate no larger than 2.97 millimeters per decade (Figure 6), making the dry season even more severe.

For this region, no other month recorded a significant trend in total rainfall in the course of the last three decades. But Table 2 shows that another four months might join the list of purely decreasing rainfall if a 10% significance level (and a 90% confidence level) were considered acceptable: January, June, October and November. This simple exercise in sensitivity analysis reveals a more general picture of serious decline in the area's rainfall.

Discussion and Conclusions

Although the Mann-Kendall test is robust, it is important to remember that it is not universal, so the double trend analysis presented above is highly recommended in order to ensure accurate inferences regarding the evolution of climate variables.

It can be said that the statistical evidence of decreasing

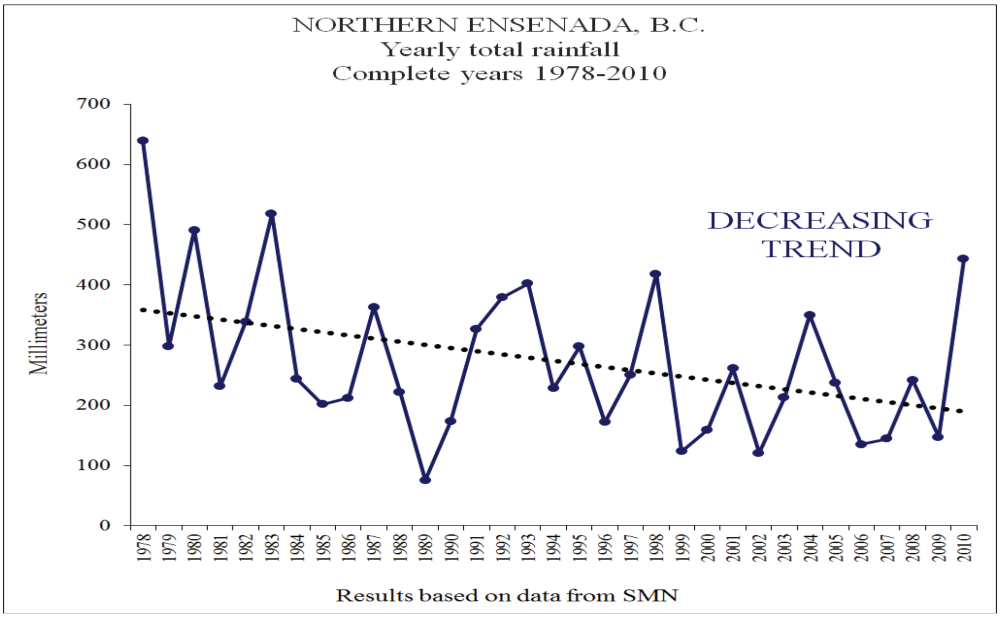


Figure 4: Yearly total rainfall 1978-2010

rainfall in the northern part of Ensenada during the period 1978-2011 is conclusive. So is the proof that the change is essentially due to a significant decline in rainfall during the months of March (rainy season) and September (dry season).

It is important to assess the impact of this observed climate change, as it represents a severe risk for life in general and in particular for human tasks in northern Ensenada, including agriculture, livestock and fisheries. Actions to optimize the area's current water management may include wastewater reuse, seawater desalinization, crop substitution and upgraded forms of irrigation, but they might not be robust enough to ensure a reliable water supply, health, agriculture and food security for the area's growing population (Bates et al., 2008).

Finally, it is advisable to apply the long-term methodology presented above to determine whether northern Ensenada has experienced an increasing number of droughts; a decreasing number of floods (Hossain et al., 2013); a warming of its surface; decreasing local dam

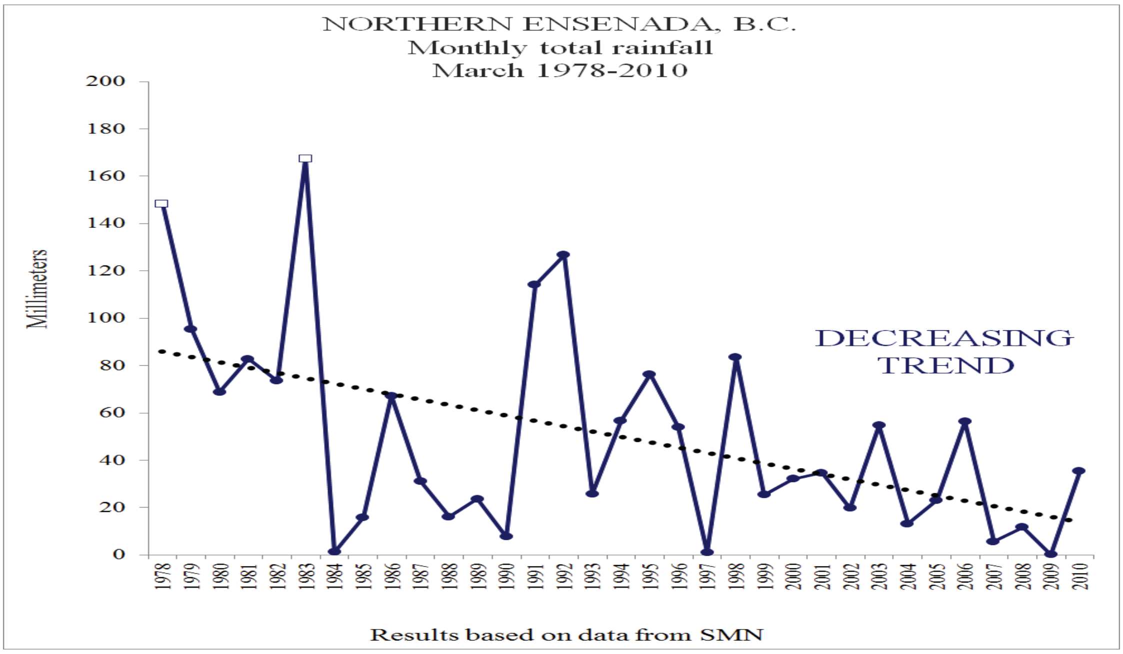


Figure 5: Total rainfall in March 1978-2010

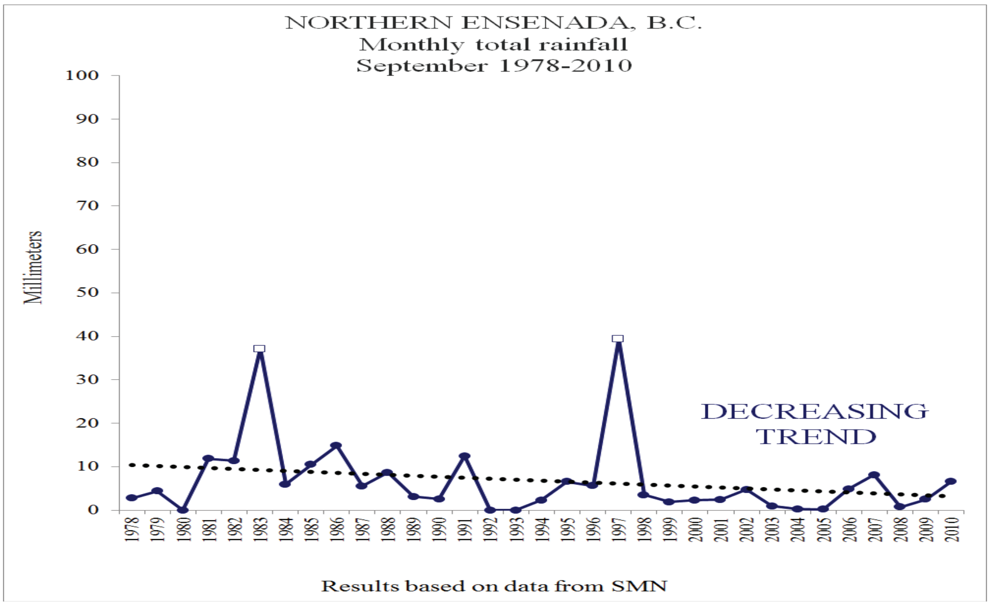


Figure 6: Total rainfall in September 1978-2010

storage; net aquifer depletion. These variables are also worth analyzing for the entire state of Baja California, or for a larger and possibly international surface.

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