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A Teaching Framework for Engineering Risk Estimation under Climate Trends*

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Estimation of risk during the lifetime of a project is an integral component of engineering design. Often, the concept of the "return period", which relates to the realization of the risk, is taught in upper-level courses, especially in the context of structures experiencing random environmental loads. In recent years, it has been recognized that trends in the underlying data, in addition to the inherent randomness, may play an important role in estimating risks for engineering design. While the research community is attempting to accommodate this non-stationarity in risk estimation, the urgency arising from climate trends requires new graduates and practitioners to understand the methods involved. Under these conditions, the widely used concepts of return periods and the consequent risks to a structure has to be examined in a new light. Our goal is to develop a framework that can be used in teaching selected undergraduate courses, master's level courses, and professional continuing education courses to enable the student to make practical engineering calculations. Since the mathematical formulations can be intimidating, we demonstrate a simple Excel-based teaching framework that instructors can utilize to present the underlying ideas in an intuitive manner and to enable students and practitioners to easily implement the concepts. Attention is also devoted to communicating the results to concerned parties. Student performance data relating to two assignments over two years indicated that, while only 40% solved the first assignment correctly, owing to a better understanding with the passage of time, 65% of the students demonstrated full comprehension on a second assignment which was based on individualized datasets; the others received scores of 90% or higher. Thus, the approach provided here appears to be suitable for classroom education.

Keywords: return period; non-stationarity; risk

1. Introduction

The concept of "return periods" appears in many engineering applications concerned with structures that must withstand random environmental forcing. For example, a seawall or a levee may be designed to withstand a 200-year return period (RP) water level or a bridge may be designed to withstand, say, the 100-year flood. The term "100-year floodplain", for instance, is used to demarcate the region around a waterway that would be inundated by a 100-year flood and occurs in everyday use in the context of home-owner insurance. Other examples include the design of breakwaters, oil platforms, and skyscrapers which require RP thresholds for environmental loads such as wave heights and wind speeds [1–3].

Even though frequent references to this term are made by the media to describe extreme wind, rainfall, or storm surge events, considerable confusion prevails among the general public and uninitiated students about the meaning of the term [4, 5]. Frequently the 100-year event is mistakenly viewed as the largest event in 100 years. Several websites and informational documents, including some produced by government agencies, may be found on the internet that attempt to remedy related misunderstandings [6–10].

Formal engineering courses in water resources engineering or coastal/ocean engineering do of course provide the correct interpretation. Many textbooks [11, 12] explain that RP relates to the probability of exceedance of a given threshold; this probability is estimated using historical data (measurements or modelled hindcasts) along with a suitable extreme value model. Often textbooks in water resources and coastal/ocean engineering [11–18] describe, for the sake of simplicity, the RP as the reciprocal of the estimated probability, which is intuitive, i.e. a 50-year event corresponds to an event (say a wind speed) that has a 2% probability of being exceeded in any year. Other advanced textbooks [1, 19, 20] provide a more formal description in statistical terms, viz. the RP is the expected waiting time between exceedances of that wind speed, i.e., the average (or "expected") time interval between occurrences of that magnitude. With either description, the probabilities can be used to estimate the risk of the event being exceeded over the lifetime of the structure.

In recent years, there has been a growing recognition of the fact that the data on which the excee-

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dance probabilities are based may contain, in addition to the inherent randomness, underlying trends. Such trends, which render the data "non-stationary", may typically arise from climate change or long term (decadal) oscillations and must be accommodated. In fact, the storm surge barriers on the River Thames near London have recently been redesigned with the effects of climate trends included. Similarly, in the US, the National Oceanic and Atmospheric Administration intends to update all floodplain maps ("NOAA Atlas14") based on a recognition of non-stationarity in the data [21]. When probability estimates are non-stationary, the estimation of risks and return periods for practical engineering design must be seen in a new light, relative to what is presented to engineering students in textbooks. In fact, even the meaning of the term "return period", so commonly used, may become specific [5, 22].

At present, much of these developments constitute the realm of research publications [23, 24]. However, given the importance of the topic as well as its practical engineering implications, it is felt that teaching material must be developed. The purpose of this paper is to demonstrate a framework, based on simple explanations and Excel-based calculations, that can be incorporated into both classroom education and workshops for practitioners.

In a traditional undergraduate engineering curriculum, topics related to return periods, probabilities of occurrence, and risk are typically covered in the third or fourth year (in courses such as Water Resources Engineering or Coastal Engineering, as noted earlier). In these courses at most one or two weeks may be devoted to these topics. Given the time constraints during a typical semester, we do not propose that the contents of this paper replace what is traditionally taught. At the level of the traditional required undergraduate course, we propose that the instructor merely alert the students to the fact that traditional concepts may be changing in fundamental ways. However, elective courses, senior-year capstone design courses (which involves some level of self-learning and team-work), and postgraduate level courses (including first year M.E. or M.Sc. level courses), especially at emerging programs such as the consortium-based Erasmus Mundus degree program in Flood Risk Management, or those offered independently by various institutions (e.g., Brunel University, University of Chester, and others), should readily be able to accommodate these topics. In fact, the material described in this paper has been taught in a postgraduate level Coastal Engineering course at Texas A&M University for the past two years.

While covering this material, it is important to recognize the difficulty that many students have with statistical concepts. The reasons for this are widely discussed in literature [25–27]. In the US, most engineering curricula offer a generic course in Probability and Statistics in the sophomore year, but there is little reinforcement of the material in subsequent courses prior to the students enrolling in Water Resources or Coastal/Ocean Engineering courses, typically much later. In some cases, the overall exposure itself to probabilistic methods is lacking both in the student community and among practitioners [28, 29]. In light of this, our description eschews the extremely theoretical statistical formulations contained in research papers. Rather, we rely on an intuitive approach, as stated earlier, and the use of Excel and simple but practical examples. Spreadsheets can be extremely effective for teaching complex engineering topics [30]. Importantly, differences between the traditional method and the non-stationary method are highlighted in the context of presenting the engineering calculations to clients and managers.

2. The Technical Problem

As an example, students can be exposed to the practical engineering problem of estimating, say, the wave height corresponding to an RP of 100 years at a coastal location. (Depending on the

Owned and maintained by National Data Buoy Center
3-meter foam buoy
SCOOP payload
29.232 N 94.413 W (29°13'54" N 94°24'45" W)

Site elevation: sea level
Air temp height: 3.7 m above site elevation
Anemometer height: 4.1 m above site elevation
Barometer elevation: 2.7 m above mean sea level
Sea temp depth: 1.5 m below water line
Water depth: 16.2 m
Watch circle radius: 52 yards

Fig. 1. NOAA buoy 42035 (courtesy: ndbc.noaa.gov).

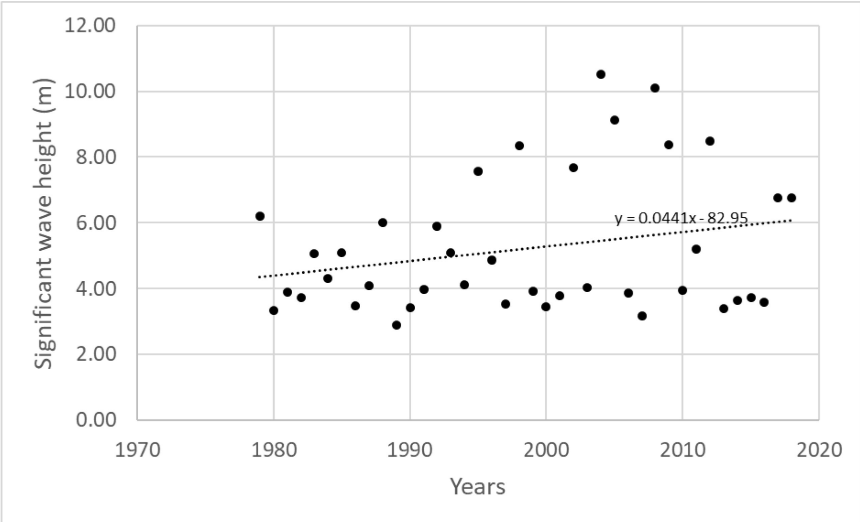

Fig. 2. Annual maximum significant wave heights for buoy 42035 (courtesy: ndbc.noaa.gov).

course, the instructor can select data relevant to the field). We choose buoy 42035 (Fig. 1) near Galveston in the Gulf of Mexico, for which hourly data for the period 1973–2018 are obtained from ndbc.noaa.gov.

For extreme value analysis, a subset containing the annual maxima is often used. An alternative is to select the maxima from individual (storm) events. The year and the corresponding annual maxima (say H) shown in Fig. 2 are recorded in Excel. Although not necessary at this stage, it is worthwhile noting that a best fit curve shows a trend, which suggests perhaps that a non-stationary approach is required.

3. Probability of Exceedance: Stationary Conditions

In the traditional approach, the data pertaining to maxima in a chosen interval (e.g., the annual maxima in Fig. 2) are fit to a suitable extreme value distribution. There are several of these and the appropriate choice is also a matter to be considered, but that issue is not related to the topic at hand. For the present, let us provide the student with a fairly standard distribution, viz. the Gumbel distribution, given by the cdf:

$$P(H \leq H^*) = \exp\left(-\exp\left(-\frac{H^* - a}{b}\right)\right) \quad (1a)$$

or the exceedance function

$$P(H > H^*) = 1 - \exp\left(-\exp\left(-\frac{H^* - a}{b}\right)\right) \quad (1b)$$

(1a) and (1b) simply provide the probabilities of not exceeding or exceeding a specified wave height H^*. a and b are parameters that fix the geometric shape, and many textbooks go into considerable detail relating to "plotting position" formulas, probability graph paper, etc. to estimate them. We believe these approaches simply distract the student; also, they are cumbersome and unnecessary in modern times. Simply entering the data into Matlab, Minitab, or other programs and selecting the Method of Maximum Likelihood, for instance, will yield perhaps the most robust estimates for a and b. In terms of simple explanations for the students' benefit, the values of a and b so obtained represent a suitable fit of the formula (1) to the data.

In our case, using the 41 data points (note, the distribution needs only the wave heights, not the associated year), we obtain $a = 4.31$ and $b = 1.37$. A plot of the cdf based on (1a) can be produced (Fig. 3). As an aside, we note that a simple way to examine the goodness of fit of this curve is to use the "sample" probabilities for each H^* after ranking the data, i.e., for each value of H^*, one estimate of the sample probability of non-exceedance would be $i/(n+1)$, where i = the rank and n = the number of data points. This is shown in Fig. 3.

Armed with the theoretical curve in Fig. 3 or the formula (1) with a and b known, we can now obtain the H^* corresponding to any given probability of exceedance. An example for selected probabilities is shown in Table 1.

4. Return Periods

Once the threshold H^* corresponding to a given probability of exceedance is obtained (i.e., Table 1),

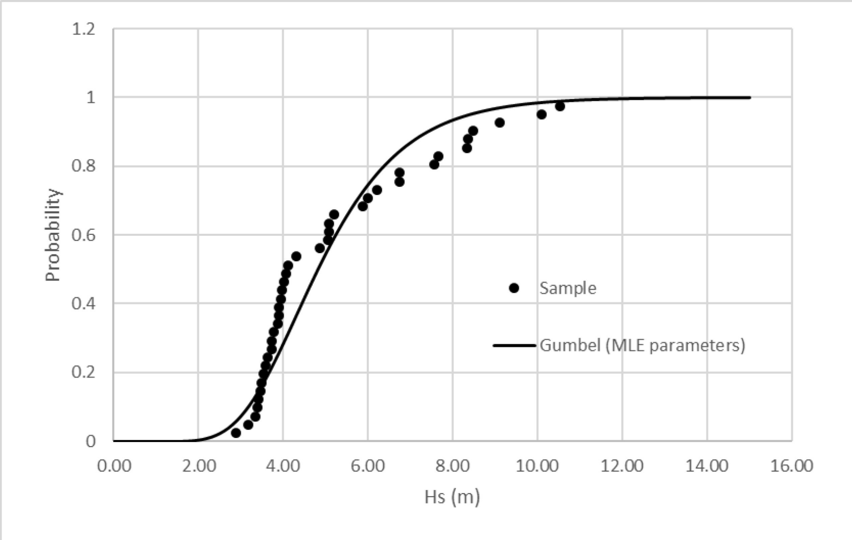

Fig. 3. cdf for the dataset of Fig. 2.

Table. 1. Wave height and probability relationship

***P* (*H* > *H**)**	***H**(*m*)**
1/100	10.62
1/50	9.66
1/10	7.40
1/3	5.55
1/2	4.81

several textbooks indicate the RP to be simply the reciprocal of $P(H > H^*)$, i.e. $T = 1/P(H > H^*)$. Thus, for example, the wave height of 10.62 m would have a RP of 100 years. Even though our dataset spanned only 40 years and contained only 40 numbers, the use of the Gumbel distribution has enabled us to estimate 10.62 m as the wave height which would be equaled or exceeded once out of 100 numbers; 9.66 m to be a similar threshold that would be equaled or exceeded twice out of a hundred numbers. Since each number occurs once in a year, it would be reasonable to say that H^* = 10.62 m would be equaled /exceeded once in a hundred years (on average), and H^* = 9.66 m twice in a hundred years. Which would imply that the RP for 10.62 m is 100 years and for 9.66 m, it is 50 years.

The same intuitive reasoning can be extended to the case of each data point representing a storm maximum (instead of the annual maximum). For the sake of argument, assume the 40 numbers in Fig. 1 represent 40 storms that occurred in 20 years (i.e., 2 storms per year on average). In this case the H^* = 10.62 m would still correspond to $(H > H^*) = \frac{1}{100}$, i.e., one in a hundred numbers would equal or exceed it. But since a hundred numbers would occur in 50 years, the H^* = 10.62 m would represent a RP of 50 years. H^* = 9.66 m would be exceeded twice in 50 years and would hence represent a RP = 25 years. In other words,

$$RP = \frac{1}{\lambda P(H > H^*)},$$

where λ = number of events per year. (2)

While the above intuitive linkage between P and RP is satisfactory for undergraduate courses, a more formal statistical definition of the RP is given in some texts [1, 19]. Per this definition, the RP represents the "expected waiting time" between events with the corresponding threshold. In other words, for H^*> 5.55 m, which we will call event E for convenience, P = 1/3.Thus,

- the probability of encountering event E *for the first time* in year 1 = p(X = 1) = 0.33
- the probability of encountering event E *for the first time* in year 2 = p(X = 2) = (probability of not encountering it in year 1) x (probability of encountering it in year 2) $(1 - 0.33)(0.33) = 0.222$
- the probability of encountering event E *for the first time* in year 3 = p(X = 3) $(1 - 0.33)^2(0.33) = 0.148$.
- etc.

(Here, p(X = x) denotes the probability of encountering E for the first time in year x; for convenience this will be denoted as p(x) hereafter).

If we had 100 geographical regions, say, with essentially similar wave climates but with random differences in terms of time, then:

~ 33 of them would encounter event E in Year 1
~ 22 of them would encounter event E in Year 2

$\sim$ 15 of them would encounter event E in Year 3
. . . etc.

The average waiting time would then be:

$$\frac{(1\ year \times 33\ times) + (2\ years \times 22\ times) + \cdots}{100} = \sum_{x=1}^{n} x.p(x) \quad (3)$$

where n denotes the number of years and should be sufficiently high to allow convergence. Students may be urged to perform the above calculation using Excel. They will find that if they use about 10 or more terms in the summation, the average will converge to 3 years. They will actually see the probability of the first occurrence declining with time; and they will also find that a large number of rows in Excel are needed to demonstrate that the RP = 100 years if P (H > H*) = 1/100, i.e., for H^* = 10.62 m.

While the formal definition implemented with Excel yields the same RP (obviously) as the intuitive approach it serves two purposes: it enables students to understand what is meant by the statistical "expectation" or the term "on average"; and, more important, it sets the stage for related calculations in a non-stationary environment.

5. Risk

A parameter of interest in engineering design is the level of risk of the structure encountering the design environmental loading. Estimating this is straightforward, once the probabilities of exceedance for the different thresholds are determined. For example, if the design life of the levee is 50 years and it is designed to withstand $H = 10.62$ m (i.e., the 100-year event), the probability that this event does not occur in each of the 50 years is $(1 - 0.01)$. Hence the probability of it not occurring during the design life is $(1 - 0.01)^{50} \approx 0.61$, which is known as "reliability" or "non-encounter probability". The risk of encountering at least one event equaling or exceeding $H = 10.62$ m in the 50 years is called "risk".

6. The Non-Stationary Case

For simplicity let us consider the case of H^* = 5.55 m which had a probability of exceedance obtained from the data and eq(1) of 1/3 (Table 1); the corresponding stationary RP was 3 years. Let us now assume that the wave climate is intensifying. Deferring for the moment the procedures relating to estimating time varying probabilities, let us assume that $P(H > 5.55\ m)$ *increases* with time, and that these probabilities in various years are given, say:

$$\left.\begin{array}{r} P(H > 5.55\ m)\ \text{in year 1} = p1 = 0.333 \\ P(H > 5.55\ m)\ \text{in year 2} = p2 = 0.343 \\ P(H > 5.55m)\ \text{in year 1} = p3 = 0.353 \\ . \\ . \\ . \\ etc. \end{array}\right\} \quad (4)$$

Obviously, we cannot now resort to the intuitive approach to estimate the RP. The "expected waiting time" must be determined as follows. (Note, the principles are the same as in Section 4).

The probability of exceeding H= 5.55 m for the first time

in year 1 = 0.333
in year 2 = (1 – 0.333) (0.343) = 0.229
in year 2 = (1 – 0.333) (1 – 0.343) (0.353) = 0.155 (5)
_ _ _ _ etc.

The average waiting time would then be 1(0.33)+ 2(0.229) + 3(0.155) + $\cdots$, which, using Excel, can be shown to converge to 2.85 years (Fig 4a). Note, columns A and B contain given information. The Excel formula for computing probability of first occurrence in each year (row n) is shown in column C of Fig. 4b and is computed as

$$p(n) = \frac{p(n-1)}{P(H > H^*)_{n-1}} \times (1 - P(H > H^*)_{n-1}) \times P(H > H^*)_n \quad (6)$$

The formulas in column C may also be confirmed by examining the relations in (5). The return period calculation is implemented using columns D and E and is continued till convergence is observed in column E, to a value of 2.854.

Understandably, the RP is less than 3 years. The actual effect of this is demonstrated with other numbers corresponding to Table 1 later.

In terms of risk, assume the design life was 5 years. If the design (stationary) RP was 3 years, then the risk of at least one encounter in 5 years would be $(1 - (1 - 0.333)^5) = 0.875$. In the non-stationary case, though, the probability of not exceeding H^* = 5.55 m

in year 1 = 1 – 0.333,
in year 2 = 1 – 0.343,
in year 3 = 1 – 0.353,
. . .

Thus, the non-encounter probability = (1 – 0.333) (1 – 0.343) (1 – 0.353) (1 – 0.363) (1 – 0.373) = 0.113, and the risk is 1 – 0.113 = 88.7%, which, as the students should note, is *higher* than in the stationary case. Often, it is necessary to prespecify the risk, and then compute the acceptable H. In the stationary case, the formula can be easily inverted to find p and

	A	B	C	D	E
1				Return Period calculation	
2	Year x	Excedence probability in Year x P(H>H*)	Prob. Of 1st occurrence in Year x p(X=x)	x • p(X=x)	Running Sum of x • p(X=x)
3	1	0.333	0.333	0.333	0.333
4	2	0.343	0.229	0.458	0.791
5	3	0.353	0.155	0.464	1.255
6	4	0.363	0.103	0.412	1.666
7	5	0.373	0.067	0.337	2.003
8	6	0.383	0.043	0.260	2.263
9	7	0.393	0.027	0.192	2.456
10	8	0.403	0.017	0.137	2.592
11	9	0.413	0.010	0.094	2.686
12	10	0.423	0.006	0.063	2.749
13	11	0.433	0.004	0.041	2.790
14	12	0.443	0.002	0.026	2.816
15	13	0.453	0.001	0.016	2.832
16	14	0.463	0.001	0.010	2.842
17	15	0.473	0.000	0.006	2.847
18	16	0.483	0.000	0.003	2.850
19	17	0.493	0.000	0.002	2.852
20	18	0.503	0.000	0.001	2.853
21	19	0.513	0.000	0.001	2.854
22	20	0.523	0.000	0.000	2.854

Fig. 4a. Example of return period calculation under non-stationary conditions, for assumed annual exceedance probabilities.

	A	B	C	D	E
1				Return Period calculation	
2	Year x	Excedence probability in Year x P(H>H*)	Prob. Of 1st occurrence in Year x p(X=x)	x • p(X=x)	Running Sum of x • p(X=x)
3	1	0.333	=B3	=A3*C3	=D3
4	2	0.343	=B4*C3*(1-B3)/B3	=A4*C4	=E3+D4
5	3	0.353	=B5*C4*(1-B4)/B4	=A5*C5	=E4+D5
6	4	0.363	=B6*C5*(1-B5)/B5	=A6*C6	=E5+D6

Fig. 4b. Excel formulas for implementing return period calculation.

then the H^*; for example, if the acceptable risk level is 40%, then $(1-(1-P)^5)=0.4$, and $P=0.1$, so the structure would be designed for the 10-year RP event (which would correspond to H = 7.4 m, based on Table 1).

In the non-stationary case, the risk formula would be:

$$risk = 1-(1-p_1)\,(1-p_2)\_\_\_$$

which is difficult to invert; however, the use of Excel with different H^* values and the associated time-varying probabilities, enables one to avoid complex formulas and simultaneously allows students to quickly calculate the risk level and see how it changes.

In terms of Excel use, it may be useful to note that the risk (0.887 above) may also be obtained as the summation over five years of the probabilities given in eq. (5). To elucidate, the probability of at least one occurrence in 5 years =

the probability of the event happening for the first time in year 1 +

the probability of the event happening for the first time in year 2 +

_ _ _ _ _ +

the probability of the event happening for the first time in year 5.

In the case of non-stationarity, the counterpart of eq. 1 (or other extreme value distributions) may be obtained by making the parameters functions of time, i.e.,

$$P(H > H^*) = 1 - \exp\left(-\exp\left(\frac{H^* - a(t)}{b(t)}\right)\right) \quad (7)$$

For each value of t, then, we have a slightly different Gumbel distribution. An assumption, or a judgement call, based on the behavior of the data or the causes of the trends is needed to specify the form of the variation, e.g., is $a(t)$ a linear function? a quadratic function? etc. While both the parameters can be assumed to be varying with time, for demonstration, here we assume a linear variation only in a (i.e., $a = a_0 + a_1 t$ and b is taken to be constant over time). Unlike the stationary case, the values of t are now needed along with the corresponding annual maxima (Fig. 1); the maximum likelihood (or other method) must return three values, a_0, a_1, and b. This can be done conveniently using the R-code package to which many students are exposed during the undergraduate curriculum (especially if they take a course in Probability and Statistics). If the use of the R package is deemed too time-consuming, the instructor can provide some approximate values to enable the students to pursue other calculations of importance to planners.

7. Presenting Results

In the case of the data used in this paper (Fig. 1), the R-code yields $a_0 = 4.066$, $a_1 - 0.012$, and $b = 1.372$. Thus, eq. 7 represents a relation between t, $P(H > H^*)$ and H^*, and if two of the quantities are known, the third can be determined. For example, corresponding to the stationary 50-year H^* of 9.66 m, we have $(H > H^*)_{t=1} = 0.017$, $P(H > H^*)_{t=20} = 0.02$; similarly for $H^* = 10.62$ m, we have exceedance probabilities as shown in Table 2.

The instructor may wish to alert the students to the increasing probability, with the passage of time, of exceeding H^* = 10.62 m. It should also be noted that, in practice, it might be necessary to limit the increasing or decreasing trend for a certain period in order to be reasonable. (If annual probabilities continuously increase or decrease indefinitely, then the analyses may yield improbable or meaningless results). If Excel is used to perform the calculations shown in Table 2 (for all values of t), then the resulting columns (t (years) and p) can be used as described in Section 4 to obtain a return period- the summation will converge to ~69.5 years. Similarly,

Table 2. Probability and time relationship

***t* (years)**	***P* (*H* > 10.62 *m*)**
1	0.0085
20	0.01
25	0.0105
40	0.012
50	0.013
100	0.02

H^* = 9.66 m (corresponding to a stationary RP=50 years), yields an RP of ~42 years.

At times, the 100-year event, for example, is shown in the literature to have different values for different years. This implication, that the value corresponding to a given RP is a function of t, is misleading. As can be seen above for H* = 10.62 m, the RP converges to 69.5 years (expected waiting time, as described above). Thus the 69.5-year wave height is 10.62 m and is not a function of time. What is actually implied is that the probability of exceedance is increasing with the passage of time, and rather than provide this probability, its reciprocal is provided and interpreted (incorrectly) as an RP; as noted earlier, $RP \neq \frac{1}{p}$ in the non-stationary case. Which highlights the importance of communication, a skill that the Accreditation Board for Engineering and Technology in the US requires degree programs to instill in students. One could take this to mean that after the calculations are performed, the results should be presented in a way beneficial to the planner/designer/investor/manager.

Indeed, there have been many questions raised about the usefulness of the term "return period" in the non-stationary context. Alternative definitions have also been provided [22] and some have noted that it causes even more confusion in the non-stationary case than it does in the stationary case. Further, it provides no meaningful information to the planner [31]. In contrast, focusing on the risk profile is far more useful [23]. For example, Table 2 provided earlier and Fig. 5 show how the risk of encountering an H^* = 10.62 m increases with time. Plots such as Fig. 5 can be made for different values of the thresholds.

The other option for communicating results is to select a probability of exceedance, say 1% for any year, and compute the wave heights corresponding to it. Eq. 7 would yield the results shown in Table 3.

Note the increase in H^* with the passage of time for the same risk. A "constant risk" plot, based data such as that shown in Table 3, can be produced for various risk levels (Fig. 6).

Finally, the encounter probability during the structure's lifetime can also be computed with Excel. Assume the design H^* = 10.62 m (corresponding again to a stationary RP of 100 years) and that structure's anticipated design life = 20 years. The risk of encountering this threshold can be computed as described in Sec. 6, and the Excel calculations yield a risk of 23.4%, as shown in Fig. 7(a, b). Thus the 23.4% "design life level" is 10.62 m (following the terminology recommended by [23] and endorsed by others). If this risk is deemed unacceptable, the calculations can be repeated with a different H. (By way of comparison, the

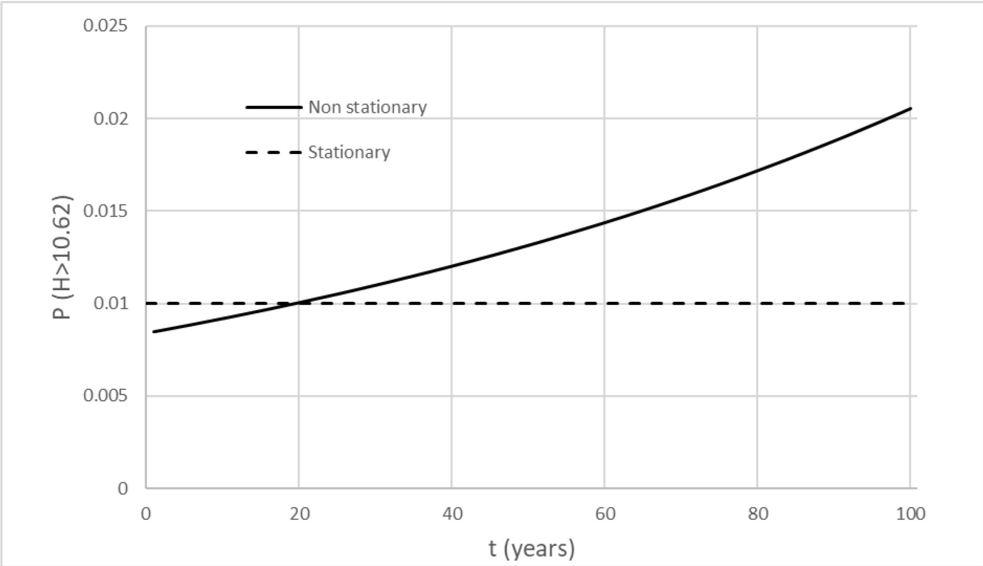

Fig. 5. Probability of exceedance of H* = 10.62m in different years.

Table 3. 1% annual exceedance thresholds with the passage of time

t (years)	*H** (*m*)
1	10.39
20	10.62
40	10.87
60	11.12
80	11.36
100	11.62

stationary calculation yields a risk of $1 - (0.99)^{20} =$ 18.2%

In the example shown in Fig. 7, we have made one adjustment to the calculations relative to the simple example in Section 6. There, the probability of first occurrence was computed for each year, starting from year 1. In the case of Fig. 7, we assume that the first year of the project is year 41, and the previous 40 years provide the data for making risk calculations; risk calculation is done for a project that has a design life from year 41 to year 60. i. e. year 41 would represent the "present" when the life of the structure begins. This is considered in computing the exceedance probability of the event in each year (i.e., in cell B43, the parameter *a* used in the Gumbel exceedance formula is $a_0 + a_1 * 41$). However, the probability of first occurrence (Column C, Fig. 7b) is calculated starting from year 41 since the probabilities of first occurrences in years prior to the start of design life are irrelevant in computing risk over lifetime of the project. Thus, the non-station-

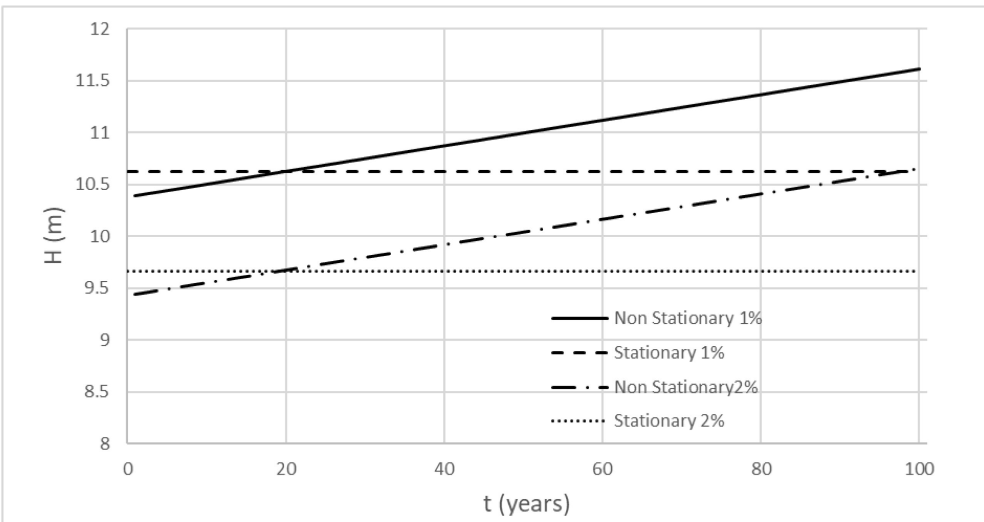

Fig. 6. Wave heights corresponding to specified annual exceedance probabilities.

	A	B	C	D	E	F
1, 2	Year x	Excedence probability in Year x P(H>H*)	Prob. Of 1st occurrence in Year x p(X=x)	Risk over design life upto Year x	Parameters	
39	37	0.0117			a0	4.0662
40	38	0.0118			a1	0.0123
41	39	0.0119			b	1.3728
42	40	0.0120			H	10.62
43	41	0.0121	0.0121	0.0121		
44	42	0.0122	0.0121	0.0242		
45	43	0.0124	0.0121	0.0363		
46	44	0.0125	0.0120	0.0483		
47	45	0.0126	0.0120	0.0603		
48	46	0.0127	0.0119	0.0722		
49	47	0.0128	0.0119	0.0841		
50	48	0.0129	0.0118	0.0959		
51	49	0.0130	0.0118	0.1077		
52	50	0.0132	0.0117	0.1194		
53	51	0.0133	0.0117	0.1311		
54	52	0.0134	0.0116	0.1428		
55	53	0.0135	0.0116	0.1543		
56	54	0.0136	0.0115	0.1659		
57	55	0.0138	0.0115	0.1773		
58	56	0.0139	0.0114	0.1888		
59	57	0.0140	0.0114	0.2001		
60	58	0.0141	0.0113	0.2114		
61	59	0.0143	0.0112	0.2226		
62	60	0.0144	0.0112	0.2338		

Fig. 7a. Example of risk calculation using Excel.

	A	B	C	D	E	F
1, 2	Year x	Excedence probability in Year x P(H>H*)	Prob. Of 1st occurrence in Year x p(X=x)	Risk over design life upto Year x	Parameters	
39	37	=1-EXP(-EXP(-($F$42-($F$39+$F$40*A39))/$F$41))			a0	4.0662
40	38	=1-EXP(-EXP(-($F$42-($F$39+$F$40*A40))/$F$41))			a1	0.0123
41	39	=1-EXP(-EXP(-($F$42-($F$39+$F$40*A41))/$F$41))			b	1.3728
42	40	=1-EXP(-EXP(-($F$42-($F$39+$F$40*A42))/$F$41))			H	10.62
43	41	=1-EXP(-EXP(-($F$42-($F$39+$F$40*A43))/$F$41))	=B43	=C43		
44	42	=1-EXP(-EXP(-($F$42-($F$39+$F$40*A44))/$F$41))	=B44*C43*(1-B43)/B43	=C44+D43		
45	43	=1-EXP(-EXP(-($F$42-($F$39+$F$40*A45))/$F$41))	=B45*C44*(1-B44)/B44	=C45+D44		

Fig. 7b. Excel formulae used for risk calculation.

ary risk depends both on the design lifetime and the starting point in time as opposed to the former only in case of stationary conditions. The non-stationary exceedance probabilities are computed in column B using eqn.7 and the non-stationary parameters are shown in cells F39, F40, and F41.

8. Student Performance Data and Experience

As stated earlier, after developing the material described above on the basis of various research papers, this approach was introduced at Texas A&M University during the 2021 Spring semester as part of the graduate-level course in Coastal Engineering. It was repeated in Spring 2022. The course was taught simultaneously to students at two campus locations, Galveston and College Station. While there were face-to-face lectures at Galveston, students in College Station accessed the lectures synchronously using Zoom. Also, owing to the coronavirus problems, frequently students chose to access the class on Zoom even in Galveston. Further, there was one international student, enrolled in the program, who always accessed the course from outside the US (at very late-night hours) via Zoom because the pandemic resulted in travel restrictions.

We can provide data on the performance of students on three assigned problems that required them to solve problems related to the material described above using Excel. The first two constituted one assignment. The first problem was straightforward: to show that, if the probability of exceedance of a certain water level is 1/8 each year, then return period (or rather, the average expected waiting time) would be eight years. Not surprisingly, most students were able to demonstrate this. Of the twenty-six students (in total), one did not turn in the assignment (for unknown reasons), and only two students were unable to accomplish this task (both in Spring 2021). The second problem was stated as follows: "While the sea levels are rising in many places, since 1950, sea levels off Alaska's coast have declined as much as 32 inches, according to some studies. Others indicate that the Caspian Sea and some of the Great lakes are also seeing declining water levels. At one of these locations, a project is built, but a risk assessment study is being performed. The engineer cannot assume indefinitely decreasing probabilities of a particular event, because that would drive the water levels to zero. So, one approach is to taper off or stabilize the probabilities. At this project site, the probability of a particular sea level being exceeded may be taken as 0.2, 0.175, 0.5, 0.125, 0.1 for each of the first five years (2021, 2022, 2023, 2024, and 2025) and then assumed constant at 0.1 indefinitely after that. (a) Estimate the average expected waiting time for that event, starting (i) now in 2021; and (ii) 10 years from now. (b) If the structure built today has a design life of 15 years, estimate the likelihood of encountering this event at least once (i.e., "risk") during its lifetime, and estimate this likelihood from the year 2030 onwards."

Of the twenty-five students who turned in this assignment, fifteen received scores of 80% or lower (the lowest being 65%), while the others solved the problem correctly. However, with the passage of time, owing to a better understanding and help sessions, the performance was much better on the second assignment, which was individualized. This assignment consisted of one problem where the students were asked to obtain their data for a buoy location (each student had to use a different dataset), to use "R" to estimate the linearly varying Gumbel parameters, and to then estimate quantities such as risk of exceedance in a given time period and prepare a risk plot corresponding to the stationary 100-year event. In this case, the lowest score was 90%, and seventeen of the twenty-six students were able to demonstrate completely satisfactory calculations. While the samples are obviously too small to lend themselves to rigorous data analyses, it appears that the majority of the students were able to grasp the ideas and make the necessary calculations using Excel.

9. Discussion

In the context of hydrology and flood forecasting, researchers [32] have developed a teaching module that aims to simplify students' learning experiences relative to commonly available deterministic models; additionally, it includes adjustments for climate change. We have provided a teaching framework along the same lines but focusing on statistical risks. In terms of traditional methods, it has been stated [1]: "*Selection of design wave heights on the basis of extreme wave statistics is simply made on the wishful postulation that the future wave climate during the lifetime of the structure will remain the same as in the past*". We believe students should be alerted to this notion, and the framework described here may be used to supplement current content. We recognize, as stated earlier, that time constraints may preclude full coverage of these topics in traditional required courses; however, electives as well as master's level courses can accommodate them. In fact, capstone projects involve teamwork, and in recent times, are expected to emphasize resilience, sustainability, and safety. One or more of the team members could undertake the calculations described here.

Finally, we note that the topics described here constitute an overview of the salient features. For each component, many options are available (e.g., choice of extreme value distribution, methods of selecting the data, identifying the best distribution, methods of parameter estimation, etc.) However, these details pertain to the traditional (stationary) cases as well and discussing them at length would distract from our main purpose, which has been to translate the highly theoretical statistical formulations [24, 33] into simple teaching tools.

10. Conclusions

We have demonstrated a simple framework that instructors can use to expand the educational component associated with estimation of environmental risks resulting from climate or other trends for design purposes. Data related to two semesters of student performance suggests that the vast majority of the students are able to comprehend the essential features of the statistical concepts and to adequately perform risk calculations needed for engineering design.

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