Design Life Level

quantifying risk in a changing climate

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make dyke 1.5 m higher

→ costs billions of Euros, popular protests

keep dyke as is
→ (perhaps) thousands of deaths

standard-based design ↔ risk-based design

Current practice: return levels

the 10,000-year flood is the water level $\boldsymbol{u=u_{10,000}}$ which on the average is exceeded once every ten thousand years $= 1/10{,}000$ quantile of the d. f. of the maximum flood in a year.

In a stationary climate with independent years, it follows that
$\boldsymbol{P(\text{10,000-year max}>u_{10,000}) \approx 1-e^{-1} \approx 0.63}$

Very useful and convenient indeed: One number gives you two things at once. E.g. it follows that if you design dykes to resist the 10,000-year flood, then you know that the probability of a catastrophe during 100 years is $\boldsymbol{1-e^{-0.01} \approx 0.01}$ for any 100-year period.

this doesn't make sense in a changing climate

French dams and Dutch dikes: 10,000 year return levels

10,000 years ago, there were few humans and little civilization on earth. 10,000 year from now, our world will be completely and utterly different in ways we cannot even imagine now.

Common codes: 100 year return levels

From 1913 to 2012 we have passed from a largely non-industrialized world to a post-industrial world. There has been two world wars, the Soviet Union has appeared and vanished, and China is rising to become the major superpower. Also 100 years from now the world will be completely different. But hopefully some major engineering structures will survive 100 years and more.

However interpretations like the following do make sense

The probability that an individual dam will fail next year is 1/10,000. There are (perhaps?) 650 dams in France, so “on the average” 650 x 100/10.000 = 6.5 dams will fail during the next 100 years -- but non-stationarity and dependence makes reality much more complex than this.

Current practice: return periods

the T-year Return Level $\boldsymbol{u_T}$ is the level which on the average is exceeded once every $\boldsymbol{T}$ years, and is given by

$$E(\textbf{\#exceedances of } \boldsymbol{u_T} \textbf{ in } \boldsymbol{T} \textbf{ years}) = \boldsymbol{T(1\text{-}F(u_T)) = 1}$$

the u-level Return Period $\boldsymbol{T_u}$ is the average time betweeen exceedances of the level u, and is given by

$$E(\textbf{time between exceedances of u}) = \boldsymbol{T_u} = \frac{\mathbf{1}}{\boldsymbol{1-F(u_T)}}$$

(note the relation $\boldsymbol{T_u(1\text{-}F(u_T)) = 1}$)

tempting to use in return periods also in non-stationary climate --- but this is not a good idea

Current practice: more recently

Yearly probability of exceedance: *p*% probability of exceeding in a year (corresponds to the return level $\boldsymbol{u_{1/p}}$), e.g. 0.01% probability of exceeding during the next year

(Sometimes complemented with information about the probability of exceeding during some longer time period)

In a non-stationary climate the yearly probability of exceedance changes from year to year

Hypothetical example used to introduce new concepts and tools

$$G_t(x) = e^{-(1+\xi_t \frac{x-\mu_t}{\sigma_t})_+^{-1/\xi_t}}$$ d.f. of highest water level in year t

$$\mu_t = 1 + 0.002t, \quad \sigma_t = 1 + 0.002t, \quad \xi_t = 0.1$$

- 0.2% increase in mean per year – could e.g. be caused by an increase in mean water level
- 0.2% increase in scale per year – could e.g. be caused by climat becoming more variable

New concepts and tools

the basic information needed for engineering design should consist of: (i) the design life period (e.g., the next 50 yrs., say 2015-2064); and (ii) the risk (e.g., 5% chance) of a hazardous event (typically, in the form of the hydrologic variable exceeding a high level)

Design Life Level

Minimax Design Life Level

complemented by

Risk plots

Constant risk plots

Design Life Level

Design Life Level: the T_1 - T_2 p% extreme level

T_1 = start of the design life period
T_2 = end of the design life period
p = risk the level is exceeded during the design life period.

Technical quantification/communication:

“the 2015-2064 5 % highest water level is 11.5 m”

Communication with the public:

”there is a 1 in 20 risk that the biggest flood during 2015-2064 will be higher than 11.5 m.”

Minimax Design Life Level

Minimax Design Life Level: the *T1 -T2 p*% bounded yearly risk level.

T_1 = start of the design life period
T_2 = end of the design life period
p = maximal risk the level is exceeded during any one year in the design life period.

Technical quantification/communication:

"the 2015-2064 0.1 % bounded yearly risk water level is 12 m"

Communication with the public:

"the risk that there will be a bigger flood than 12.0 m is less than 1 in 1000 for each year in the time period 2015-2064"

Risk plot

fixes a level and shows how the risk of exceeding this level varies for the different years in the design life period

Constant risk plot

fixes a probability and for each year in the design life period displays the level which is exceeded with this probability

Results for hypothetical example

Design Life	Prob.	Design Life Level	Return Level *(2015 climate)*	EWT	EWT *(trend stopped)*
2015-2064	0.05	11.5	10.9	251	788
2015-2064	0.01	15.2	14.4	431	3839
2065-2114	0.05	12.6	10.9	262	1008
2065-2114	0.01	16.6	14.4	453	5002

Return levels are for T = 975 and T = 4975, respectively. EWT is expected waiting time until first exceedance

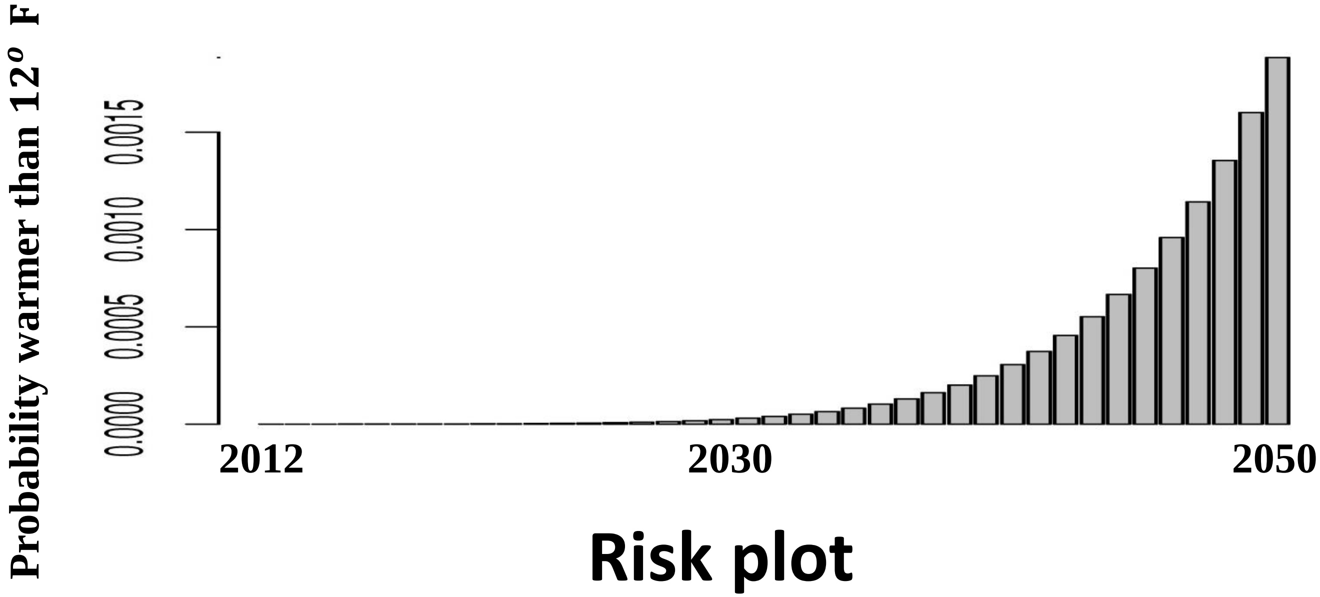
Fort Collins
high yearly minimum temperature

The 2012-2050 10% probability warmest winter has a minimum temperature of 12^{o} F

The 2050-2090 10% probability warmest winter has a minimum temperature of 16^{o} F

The statistical uncertainty is $\pm\ \mathbf{4^{o}}$ F

Fort Collins
high yearly minimum temperature

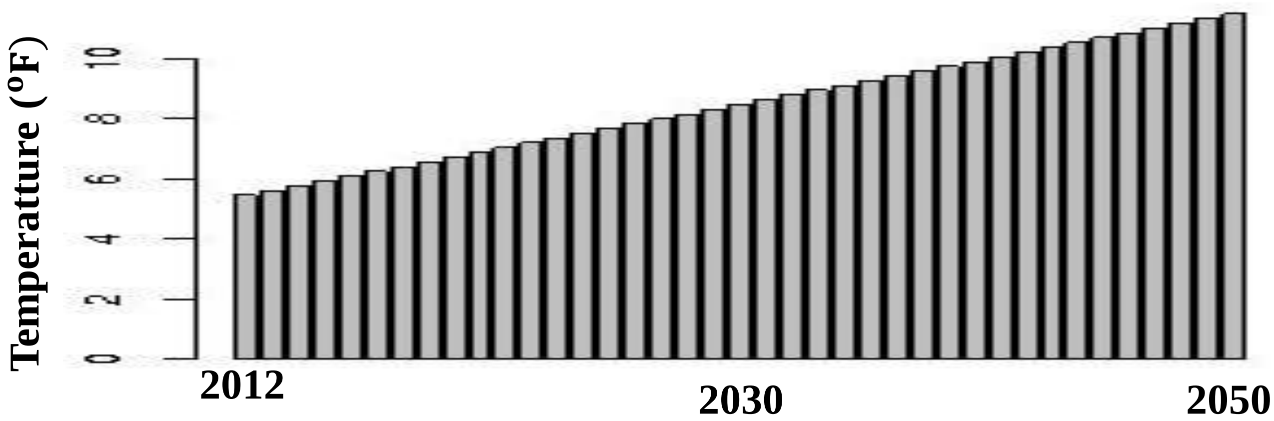


Risk plot

(Remember: ”The 2010-2050 10 % probability ”warmest winter” has a minimum temperature of 12° F”)

Statistical uncertainty → Color bands?

Fort Collins
high yearly minimum temperature



0.2% constant risk plot

Statistical uncertainty → Color bands?

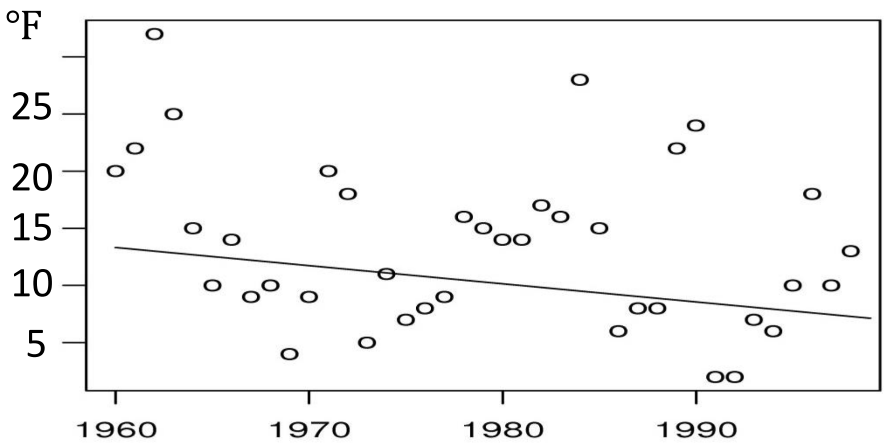
Fort Collins

~~the 2020 12^0 highest minimum winter temperature return period~~

- Intrinsically stationary concept
- Depends strongly on what happens after design life
- Means different things in different nonstationary scenarios
- Doesn’t describe variation around mean

\+ One doesn’t have to specify a probability, just a level

Fort Collins: standard data analysis (R package: extRemes)

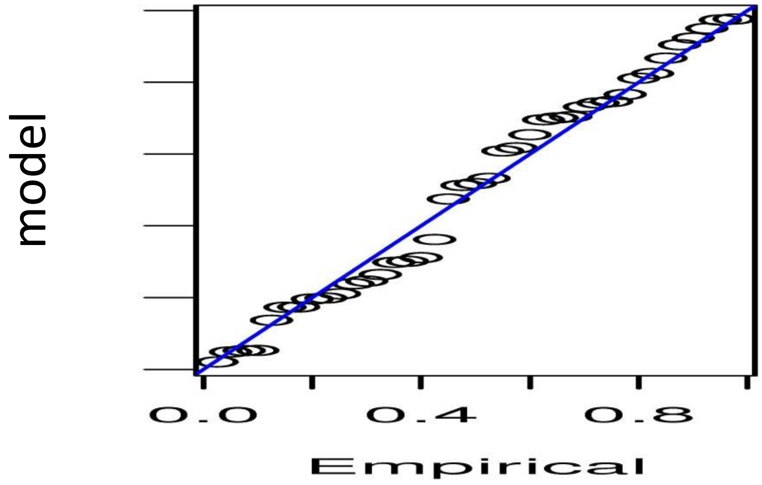


neg. yearly minimum temperatures

$$X \sim \exp\left(-\left(1+\gamma\frac{x-\mu_t}{\sigma}\right)^{-1/\gamma}\right)$$

$$\mu_t = \alpha + \beta t$$

$$\hat{\alpha} = 334$$
$$\hat{\beta} = -0.15$$
$$\hat{\sigma} = 5.6$$
$$\gamma = -0.052$$



$$\sum = \begin{matrix} -80.4 & 4.28\text{e-}02 & 5.69 & -1.284 \\ 0.0428 & -2.25\text{e-}05 & -0.00283 & 0.000640 \\ 5.69 & -2.83\text{e-}03 & 0.242 & 0.0283 \\ -1.28 & 6.40\text{e-}04 & 0.0283 & 0.00333 \end{matrix}$$

Estimation of Design life Level

$$\boldsymbol{P} = \boldsymbol{P}(\boldsymbol{y};\boldsymbol{\theta}) = \boldsymbol{P}(\boldsymbol{y};\boldsymbol{\alpha},\boldsymbol{\beta},\boldsymbol{\sigma},\boldsymbol{\gamma})$$

$= \boldsymbol{P}($**2012-2050 warmest winter has a minimum temperature > y**$)$

$$= \mathbf{1} - \left(\mathbf{1} - \exp\left\{-\left(\mathbf{1} + \boldsymbol{\gamma}\frac{-\boldsymbol{y}-\boldsymbol{\mu}_{\mathbf{2012}}}{\boldsymbol{\sigma}}\right)^{-\frac{\mathbf{1}}{\boldsymbol{\gamma}}}\right\}\right) \cdot \ \ldots$$

$$\cdot \left(\mathbf{1} - \exp\left\{-\left(\mathbf{1} + \boldsymbol{\gamma}\frac{-\boldsymbol{y}-\boldsymbol{\mu}_{\mathbf{2050}}}{\boldsymbol{\sigma}}\right)^{-\frac{\mathbf{1}}{\boldsymbol{\gamma}}}\right\}\right)$$

solve $\mathrm{P}(y;\widehat{\theta}) = 1/10$ for y

→ $\widehat{y}_{1/10} =$ the ***2012-2050 10%*** **probability warmest winter minimum temperature (=** 12^o **F)**

Delta method

$$P(y;\theta) = 1 - (1 - \exp\{-(1+\gamma\frac{-y-\mu_{2012}}{\sigma})^{-\frac{1}{\gamma}}\}) \cdot \ \ldots$$

$$\cdot\ (1 - \exp\{-(1+\gamma\frac{-y-\mu_{2050}}{\sigma})^{-\frac{1}{\gamma}}\})$$

$$\hat{y}_{1/10} = \mathrm{q}\left(1/10; \hat{\theta}\right) = P^{-1}(1/10;\ \theta)$$

$$\nabla q = \left[\frac{\partial q}{\partial \theta}\right] = \left[\frac{\partial q}{\partial \alpha}, \frac{\partial q}{\partial \beta}, \frac{\partial q}{\partial \sigma}, \frac{\partial q}{\partial \gamma}\right]$$ ← compute numerically

$$V_{\varphi} = [\nabla q^{T} \sum \nabla q]_{\hat{\Theta},\ 1/10}$$

→ confidence interval for $y_{1/10}$

Parametric bootstrap

- simulate $\varepsilon_{1960}, \ldots, \varepsilon_{1999}$ from $\exp(-(1+\hat{\gamma}x)^{-1/\hat{\gamma}})$
- compute $y_{1960} = -(\hat{\mu}_{1960} + \hat{\sigma} \cdot \varepsilon_{1960}), \ldots, y_{1999} = -(\hat{\mu}_{1999} + \hat{\sigma} \cdot \varepsilon_{1999})$
- estimate the *2012-2050 10%* probability warmest winter minimum temperature from $y_{1960}, \ldots, y_{1999}$

Repeat many times, and use resulting sample of estimates to compute confidence interval for the *2012-2050 10%* probability warmest winter minimum temperature

Uncertainties

Statistical uncertainties

Model uncertaincies: choice of statistical mocel; choice of trend; for GCM-s choice of spatial resolution, differential equation models, future changes in human activity

- Already in the design phase plan for later modification to make the construction more resistant, if need should arise.
- Plan for regular adjustment of rules for managing the construction.
- Plan for regular updating of risk measures as experience and knowledge increases.

Rootzen, H. and R. W.Katz (2013), Design Life Level: Quantifying risk in a changing climate, Water Resour. Res., 49, doi:10.1002/wrcr.20425.

Olsen, J.R., Lambert, J.H. and Haimes, Y.Y. (1998). Risk of Extreme Events Under Nonstationary Conditions. *Risk Analysis*, **18**, *497-510.*

Definition of return period	Formula
Inverse of the probability of failure within the year t. (Expected observations of identical years before failure.)	$\frac{1}{1-F_t(u)}$
Expected waiting time before failure at the beginning of the design life of a project.	$\sum_{1}^{\infty} kF_1(u) \cdot \ldots \cdot F_{k-1}(u)(1-F_k(u))$
Expected waiting time before failure starting at any year t during the project life.	$\sum_{1}^{\infty} kF_1(u) \cdot \ldots \cdot F_{k+t-2}(u)(1-F_{k+t-1}(u))$

F_k(u) = probability of no failure in year k

Vogel, R.M., Yaindl, C. and Walter, M. (2011). Nonstationaritry: Flood magnification and recurrence reduction factors in the United states. *J. Amer. Water Resources Ass.* **47,** 464-474.

"… Nonstationarity in floods can result from a variety of anthropogenic processes including changes in land use, climate, and water use … A decadal flood magnification factor is defined as the ratio of the T-year flood in a decade to the T-year flood today. Using historical flood data across the United States we obtain flood magnification factors in excess of 2-5 for many regions of the United States … Similarly, we compute recurrence reduction factors which indicate that what is now considered the 100-year flood, may become much more common in many watersheds."

Based on linear normal model for logarithms of annual maximum instantaneous peak streamflow

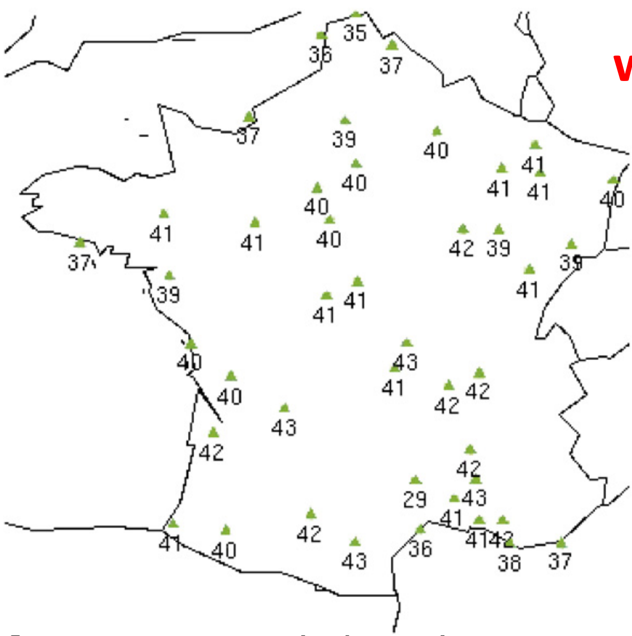
Laurent, C. and Parey, S. (2007). Estimation of 100-year-return-period temperatures in France in a non-stationary climate: Results from observations and IPCC scenarios. *Global and Planetary Change* **57**, 177–188

100- year return period: the value of u which solves

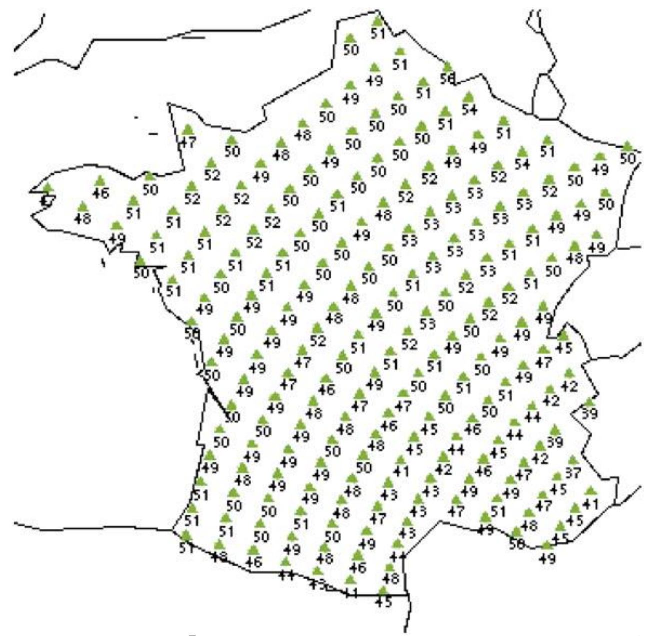
$$(\mathbf{1} - \boldsymbol{F_1(u)}) + \ldots + (\mathbf{1} - \boldsymbol{F_{100}(u)}) = \mathbf{1}$$

?

which year



100-year-return-period maximum temperatures (in °C) estimated from a non-stationary extrapolation of measurements from 1960 to 2003



100-year-return-period maximum temperatures (°C) estimated from a stationary extrapolation of ARPEGE–Climat temperatures from 2070 to 2100 (A2 scenario).

Some of the referee comments

In the U.S. communication with the public is recently being based on annual exceedance probability and the associated discharge. For example, in the communications of the National Flood Insurance Program, the term "100-year flood" has been replaced by the "one percent annual chance flood." (The Corps of Engineers has made similar changes.) In communicating with homeowners, it is also commonly stated that the probability that there will be at least one flood exceeding the one percent annual chance flood in 30 years (a common mortgage period) is 26%.

Within hydrology it is customary to assume stationarity within the expected lifetime of a structure. Other disciplines such as transportation infrastructure (and, I assume, IT networks), have had to cope with non-stationarity for a long time and hence design guidelines have been developed and implemented for quite a while.

The new concepts are not likely to be adopted by the hydrological society as a whole. The current trends are not to view the hazards in isolation, but rather to make decisions based on non-stationarity of both hazards, exposures, and vulnerabilities (terminology adapted from the recently published SREX report by IPCC WG2, http://www.ipcc-wg2.gov/SREX/). As such adoption of a separate terminology considering changes in only hazards over time will not obtain much attention.

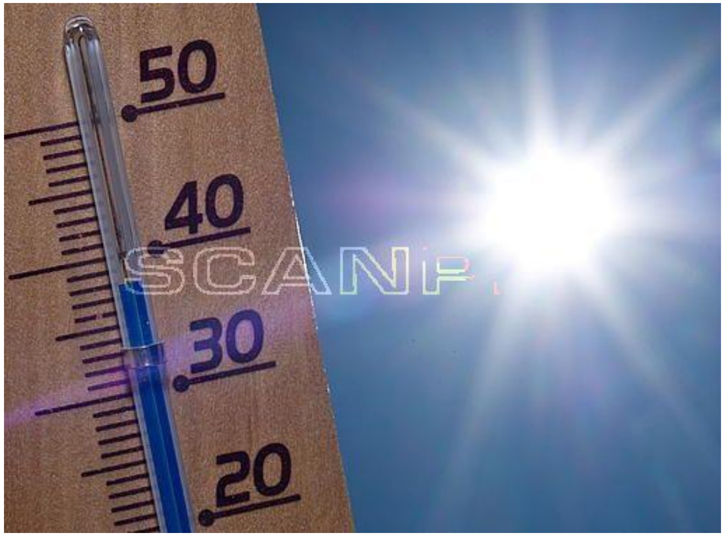
… most common design criteria are explicitly, or in a de facto sense, a “design standard”. The relevant codes of practice require infrastructure to be designed to, for example, a standard based on a “100 year” loading of some kind (water level, wind, etc). It needs to be recognised that such standards-based criteria are adopted regardless of the consequences of failure of the individual installation under consideration, and regardless of the assumed design life.

... while there is a lot being published on the desirability of risk-based concepts, invariably they are treated as a standard. ...In terms of threat to life, all comparative measures of societal and individual tolerances for risk are compared using annual exceedance probabilities in terms of financial justification, the trade-off between the costs of providing an additional level of protection against the reduced consequential level of damages are undertaken on an *annualised* basis.

…. how does one defend a specific value of probability of failure? For example, how might I evaluate the benefits of increasing the probability of failure from 0.5% to 1% over the adopted design life under changed climatic conditions? … Would it be “reasonable” to increase capital costs by 20% if it meant the probability of failure would be halved?

This exemplifies the typical kinds of issues in risk-based designt. And where threat-to-life is involved, explicit justification for the risk reduction achieved by a given capital expenditure (or adopted probability of failure) has very material legal implications (the “As Low As Reasonably Practical” or *de minimis* criterion). The accepted way of resolving these design questions is to evaluate risks on an *annualised* basis, so that the costs and benefits can be assessed in a comparable manner. Variations in design performance through time will clearly impact on any annualised measure


SCANPIX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