09 - HOW DO CLIMATE CHANGE PATHWAY ASSUMPTIONS EFFECT ECONOMIC VIABILITY AND PRIORITISATION OF FLOOD PROJECTS?

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Abstract
This paper explores the influence of how climate change pathway assumptions effect the economic appraisal and prioritisation of flood projects. We focus on flood hydrology assumptions and use anonymised case studies to demonstrate the possible effects. The paper shows how hydrology has a strong influence on economic appraisal with climate change.

We explore whether robust economic appraisal is possible when only a limited number of future climate change model scenarios are available. We test the effect of only modelling the effect of climate change at one probability and applying a probability-shift approach to derive a flood damage curve. The paper considers the effect of steep or shallow flood growth curves, abstractions and other hydrological controls to outline situations when a full set of climate change flood probability model scenarios should be analysed.

The effect of the decision to include or exclude above scheme design standard benefits is explored. Such examples are where flood storage can reduce flood levels but not fully eliminate risk in flood events above the scheme design standard.

The onset and rate of climate change effects is analysed. We compare a simple linear annual increase in flood discharge with the exponential (hockey-stick) Shared Socio-Economic pathways. Applying the economic discount rate diminishes the influence of this decision and the simpler approach can in many cases be sufficiently robust.

Multi-Criteria Analysis (MCA) is a tool commonly used for selecting the most appropriate flood risk management solution. We briefly discuss some of the considerations to take when deciding the future point in time for scoring MCA criteria. This is an important consideration as flood protection schemes encourage economic development in the protected area, which may lock-in authorities to continued protection beyond the lifetime of the flood protection infrastructure and the economic appraisal period.

We cover a conceptual review of how to include breach and failure risk within economic appraisals into the future. This is a complex issue where floodplain reconnection or upstream storage will reduce peak flood level loading to raised defence systems.

1. INTRODUCTION TO ADAPTATION PATHWAYS

Typically, a hydrology factor (e.g. +20% peak flow) can be the only climate change adjustment to an economic appraisal, with an assumed linear increase in expected losses through time to the modelled epoch. The economic appraisal and pathway analysis can therefore be overly dependent on relatively crude assumptions and does not always account for population and property value changes over that epoch. Here we explore the effect of different assumptions using modelled uplifts that are based on a probability-shift approach to the hazard grids simulated for baseline to represent the effect of increased climate change forcing. This provides a relatively low data requirement for exploring climate change dependencies, although it does require an estimate of future projected change to a forcing variable such as total rainfall or peak flow. These estimates are becoming easier to obtain, such as the CMIP5 data in Ireland[1] (albeit with very wide uncertainties), or the uplift factors in UK[2].

We apply this approach to fluvial property flooding for anonymised data using JBA's Global Flood Model[3] hazard grids, simulated for 6 present day return periods. The associated local growth curve is used in combination with the expected increase in hydrological forcing variable (rainfall total for a given duration or peak flow) to re-cast the probabilities used for the simulated hazard grids in terms of present day. These are then used in the expected annual damages (EADs) calculation and the process is repeated for different epochs. The resulting change in EAD is then fed into a typical appraisal spreadsheet and a discounting factor applied to account for inflationary pressures. The growth in EAD can be treated linearly or based on curve fitting, and in fact, for the data used there is an exponential growth. Combined with the discounting factor to account for inflationary pressures, this can result in considerably different whole-life costs over e.g. 30 years between: no climate change assumption, linear assumption and non-linear growth.

The approach is first applied to property data and then population at different locations, which can provide a more universal measure of flood risk that is less biased towards wealth. Using population, the open World Pop data has been used and combined with an Annual Exceedance Probability (AEP) map of flooding > 0m. Automating the probability shift, combined with projected climate change forcing data enables rapid appraisal of how expected annual people at risk changes through time.

Combined with a global map of flooding, this is a powerful tool for prioritising investments at the centres of greatest risk acceleration with climate change. This is without taking into account population migration and changing value of property. Population change and progressive adaptation can be emulated, for example in the UK third Climate Change Risk Assessment it was estimated there could be a 35-50% increase in national EAD for exposed property (£2bn) by 2080s under 2 degrees warming or 175% - 195% increase with 4 degrees warming for England (Sayers et al., 2018), *with continued levels of adaptation*. So, is there a possibility to increase the level of adaption using mixed approaches sooner?

The next two sections therefore explore an efficient probability-shift approach applied to property data using vulnerability curves to translate depths into damages for sample data, and then to counts of people at risk and how this can be even more efficient. Accounting for climate change demonstrates how it is important to increase adaptation across multiple measures and across the spectrum of probabilities – increasing ambition for low regrets catchment measures and property flood resilience which are low capital, rapid mitigation measures. The paper introduces two resilience analytics tools that can be used to explore trade-offs in the different mixes of measures that can provide equivalent risk-reduction, with some of these having greater co-benefits and advantages dues to their relatively rapid deployment.

1.1 Changing risk to property using a probability shift approach

Here we look at a region where there is a 20-40% increase in fluvial flooding projected by 2050, using the range to reflect uncertainty. Using the rainfall or peak flow growth curves, we can estimate future

[1] https://climateknowledgeportal.worldbank.org/country/ireland/cmip5
[2] https://environment.data.gov.uk/hydrology/climate-change-allowances/river-flow?mgmtcatid=3028
[3] https://www.jbafloodmaps.com/

reduced return periods associated with our hazard data. Therefore, in the expected losses calculation we can re-weight the losses/AEP curve and estimate the future expected losses at today's values.

However, since this is a steep ramp (in terms of increasing losses dues to climate change unless we do something), how does this interact with a typically appraisal calculation, which would previously have assumed stationarity of EAD and applied a steady discounting rate?

Here for some anonymised exposure data we compute the increase in EAD through time at present day prices using the above, but then discount due to inflationary pressure into a scheme lifetime of 30 years. The increase in EAD with time is steep but does not exhibit tipping-points in advance of which we could implement a more significant scheme.

The approach developed reduces expensive modelling costs by adjusting the current AEP to the future projected AEP for a future epoch (2050), which might be useful for medium term (e.g. 2050) mid-value schemes, or strategic investment planning, where modelling many scenarios is not tenable. If we know from climate change modelling the projected increase in a physical variable, such as rainfall total or peak flow, then we can read off the present-day equivalent of that future rainfall. In this example the adjusted Return Period and AEPs are shown for a future projected 20-40% increase in peak flows. These have been computed based on the log-linear growth curve in Figure 1 assuming 20% and 40% uplifts in the forcing variable (peak flow) to reflect uncertainty in climate projections. A horizontal line drawn in the grey zone highlights very large uncertainties in equivalent peak flow for the 'same' design event of up to 800m^3/s.

Table 1: *Re-casting future increases (20-40% uplift) with present-day equivalent return periods.*

RP (present)	AEP (present)	lnRP	Q m3/s (present)	Q m3/s (future 20%)	Q m3/s (future 40%)	lnRP	Present Day Equivalent ln(RP) using regression (R2 0.99)	Adjusted RP (20%)	Adjusted RP (40%)	Adjusted AEP for Risk Calc (+20%)	Adjusted AEP for Risk Calc (+40%)
1.6	62.5	0.470	1932.794	2319.4	2705.9	0.47	-0.753	0.80	0.47	125.3	212.2
2	50	0.693	2038.826	2446.6	2854.4	0.69	-0.579	0.98	0.56	102.4	178.4
5	20	1.609	2414.602	2897.5	3380.4	1.61	0.036	2.00	1.04	50.0	96.5
10	10	2.303	2690.459	3228.6	3766.6	2.30	0.487	3.39	1.63	29.5	61.5
25	4	3.219	3073.201	3687.8	4302.5	3.22	1.113	7.03	3.04	14.2	32.9
50	2	3.912	3384.077	4060.9	4737.7	3.91	1.622	12.73	5.06	7.9	19.8
100	1	4.605	3717.386	4460.9	5204.3	4.61	2.167	24.05	8.73	4.16	11.45
200	0.5	5.298	4075.939	4891.1	5706.3	5.30	2.753	47.68	15.69	2.1	6.4

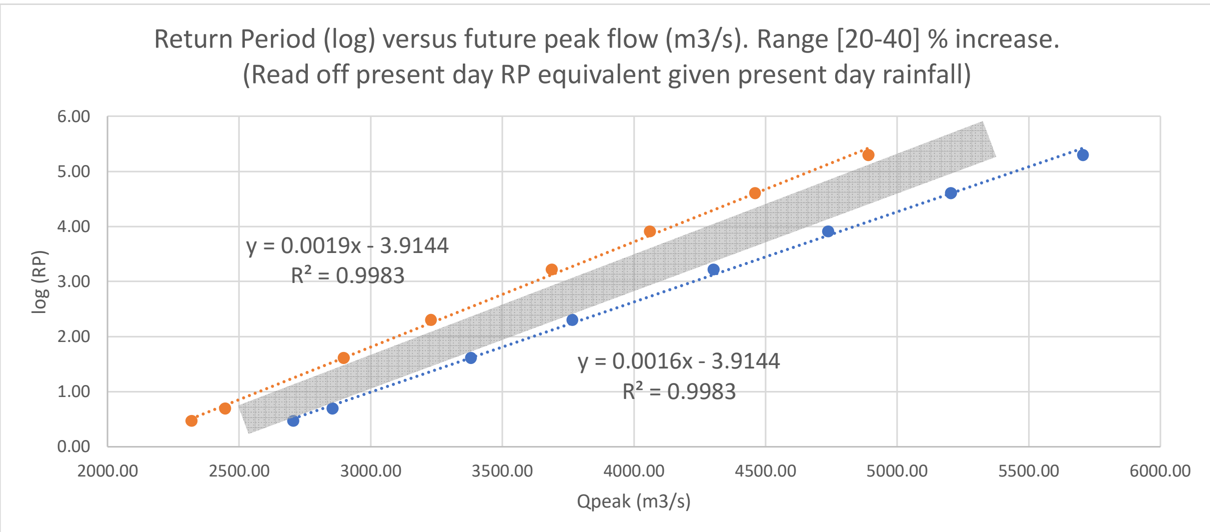

Figure 1: *Growth in Return Period (log) versus future peak flow with uncertainty (20-40% uplift).*

We have re-cast the present-day equivalent return period given we think we know how much flows have increased from e.g. climate change modelling combined with rainfall runoff predictions. These equivalent AEPs have then been used to re-cast the AEP used in the EAD calculations for anonymised data comprising >30,000 properties with 6 flood depth grids of increasing severity. The property points have been queried against each of the 6 hazard grids, and suitable vulnerability curves used to translate depths into damages. The damage versus AEP curves have been integrated to give an estimate of present-day EAD.

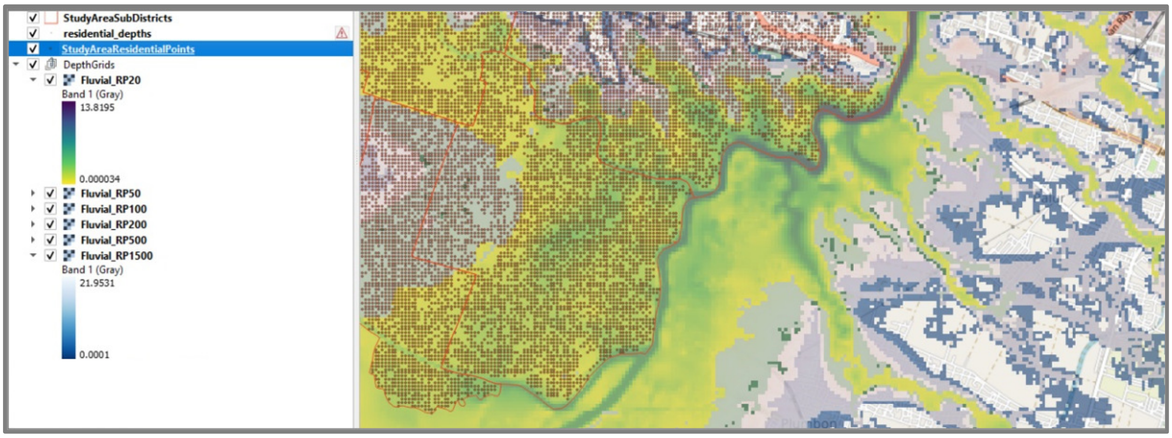

Figure 2: *Exposure data queried using overlaid depth grids (anonymised).*

The same calculation is then repeated using the same hazard data, but assuming the shifted AEP for different interval epochs (every 5 years), yielding expected future EADs and based on the 40% uplift. This results in a growth curve shown in Figure 3, but these then need to be adjusted due to inflationary pressures. It is also important to express uncertainty in this growth.

Future AEP		
Rainfall uplift	**year**	**AAL (adjusted)**
1	2020	**$ 27,527,084.47**
1.05	2023.75	**$ 34,717,821.85**
1.1	2027.5	**$ 43,870,411.78**
1.15	2031.25	**$ 54,402,992.33**
1.2	2035	**$ 66,356,223.01**
1.25	2038.75	**$ 79,757,450.38**
1.3	2042.5	**$ 94,621,706.92**
1.35	2046.25	**$ 110,952,826.82**
1.4	2050	**$ 128,744,615.57**

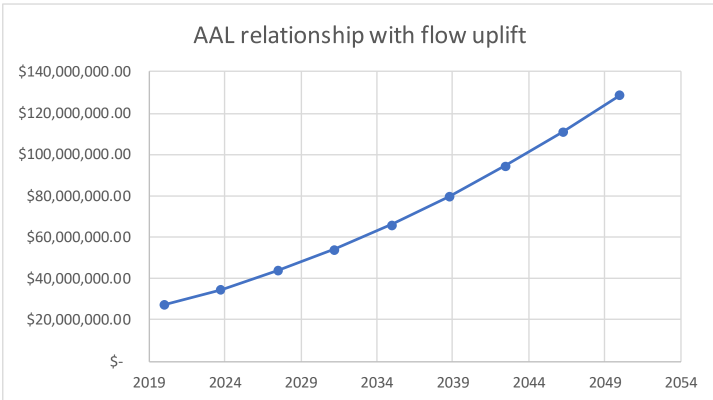

Figure 3: *How EAD vary with time horizon 2020-2050 using the probability adjustment approach.*

Traditionally we might see inflationary discounting reduce the present day EADs, and an appraisal sheet might look like Figure 4, with **present value damages: $523m** (here the discounting rate is only 3.5%).

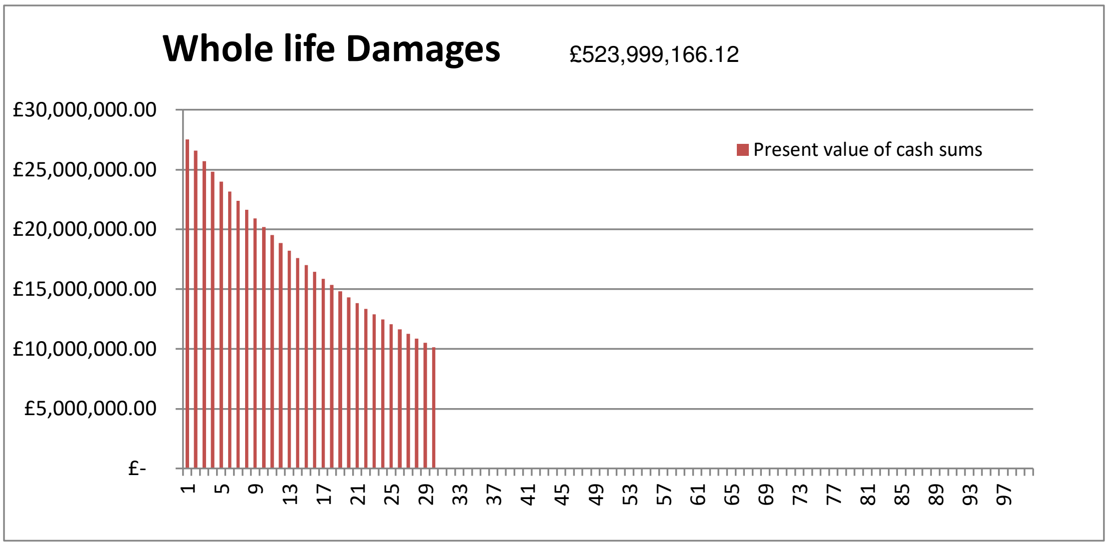

Figure 4: *Whole life damages without considering climate change.*

However, if we include the non-stationarity in the losses, there is an expected increase in losses due to increase climate forcing, the curve looks very different (Figure 5).

The present value damages do not start to ease until 21 years hence (2041) when inflationary pressure starts to reduce the present value damages, which integrated over the whole lifetime of 30 years here yield present value damages of £1,353m compared with £524m. This assumes a linearised growth in EAD. If we fit an exponential or polynomial to the growth in EAD per year (there is very high uncertainty in the coefficients) the PVD does not start to curve downwards until 2067, and there is a reduction of £200m in the estimate, with a total of £1,175m. Climate change has more than doubled the whole life damages in range (224% - 258%).

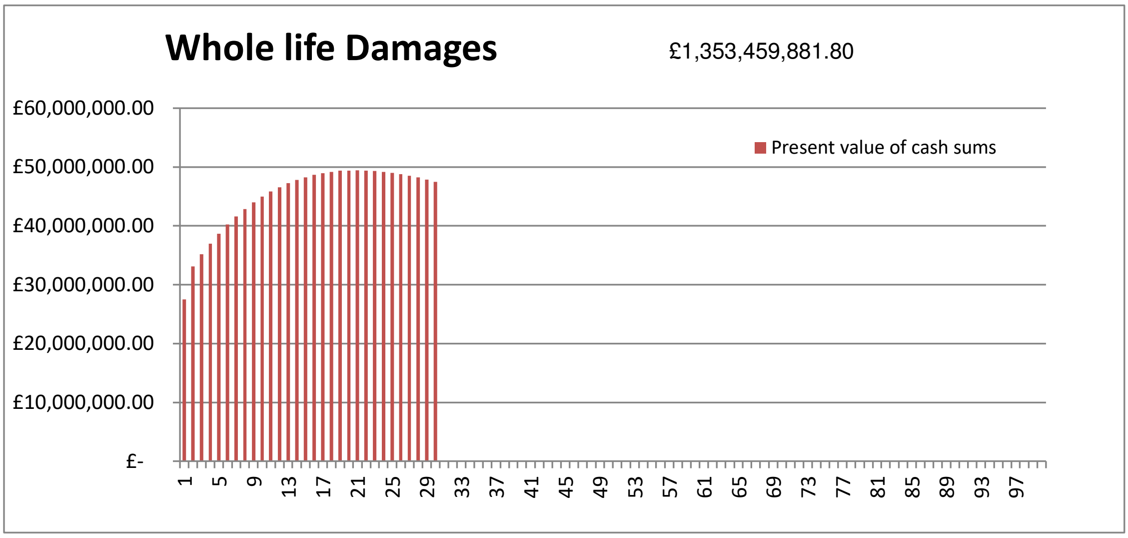

Figure 5: *Present Value Damages with Climate Change and linear growth.*

From ongoing and recent project experience in Ireland and Romania JBA has found that care needs to be taken when estimating future probabilities of present-day model scenarios for catchments with significant abstractions, reservoir operating rules and other hydrological controls influence the flood growth curve. For example, a constant abstraction rate irrespective of river discharge would mean that a 20% uplift in peak discharge results in more than a 20% increase in discharge downstream of the abstraction.

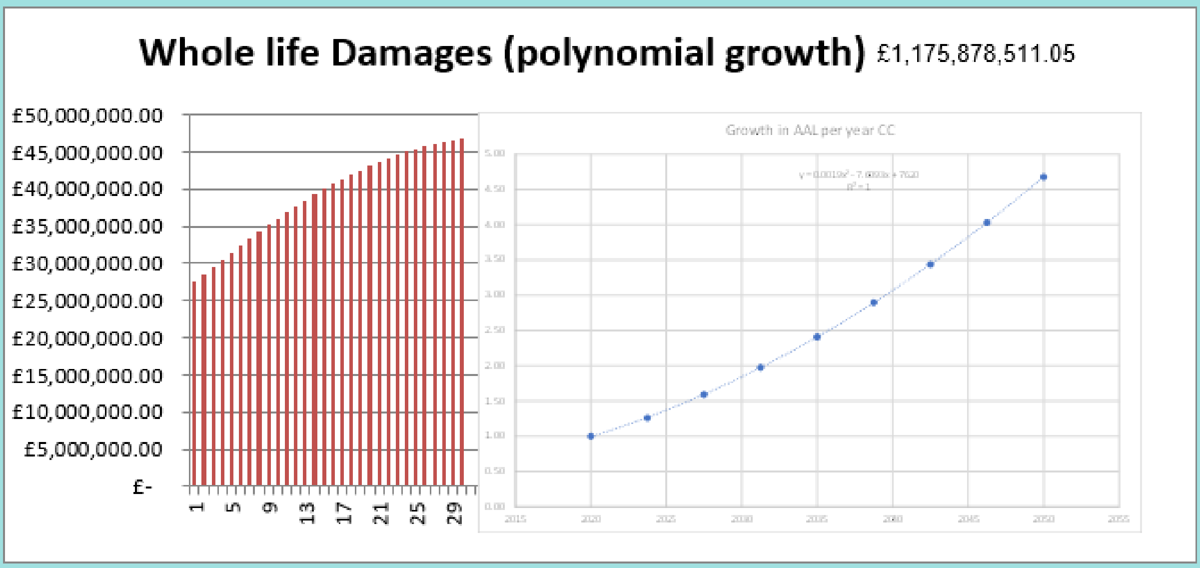

Figure 6: *Present Value damages assuming growth in EAD from Figure.*

1.2 Changing risk to people using a probability shift approach

Understanding change in economic development and population is critical to how risk will evolve into the future. An important consideration for decision makers is whether providing structural protection now locks-in a future pathway for continual maintenance, refurbishment, and extension of flood defences in response to climate change. Increasing the height of raised defences will increase the importance of monitoring and maintenance. Residual risk in terms of exposure and hazard should a higher defence fail will be greater than behind a lower flood defence. Measures which reduce peak flood level such as upstream storage or local floodplain reconnection should always be considered.

Future generations may be locked into a future where they are forced to make tricky political and financial decisions with regards reducing or continuing to provide a standard of protection. Data exists to consider these issues in our decision making now.

There are numerous sources of gridded population data around the world, including WorldPop[4], which is specifically open-data using the CCA 4 international license and Meta[5] which provides data on the Humanitarian Data Exchange[6] portal. All that is needed then, is a suite of flood hazard data for a range of AEPs. These hazards can be turned into a 30m probability of flooding raster given the associated AEPs. This can then be matrix multiplied by the population grid at the same resolution to estimate the expected annual people (EAP) at risk. The process can be repeated efficiently, and adjusted AEPs based on the regression approach in the above section re-used. The AEP map is then re-computed and multiplied by the same population grid.

Figure 7 shows that even without the population migration change into the future, the uncertain uplift in expected people at risk is quite startling [270%-560%] based on 20-40% uplift.

[4] https://www.worldpop.org/

[5] https://dataforgood.facebook.com/dfg/tools/high-resolution-population-density-maps

[6] https://data.humdata.org/organization/meta?q=population%20density&sort=if(gt(last_modified%2Creview_date)%2Clast_modified%2Creview_date

Using expected annual people at risk is arguably prone to less uncertainty than Expected Annual Damages, given the factors and assumptions deployed in depth-damage curves.

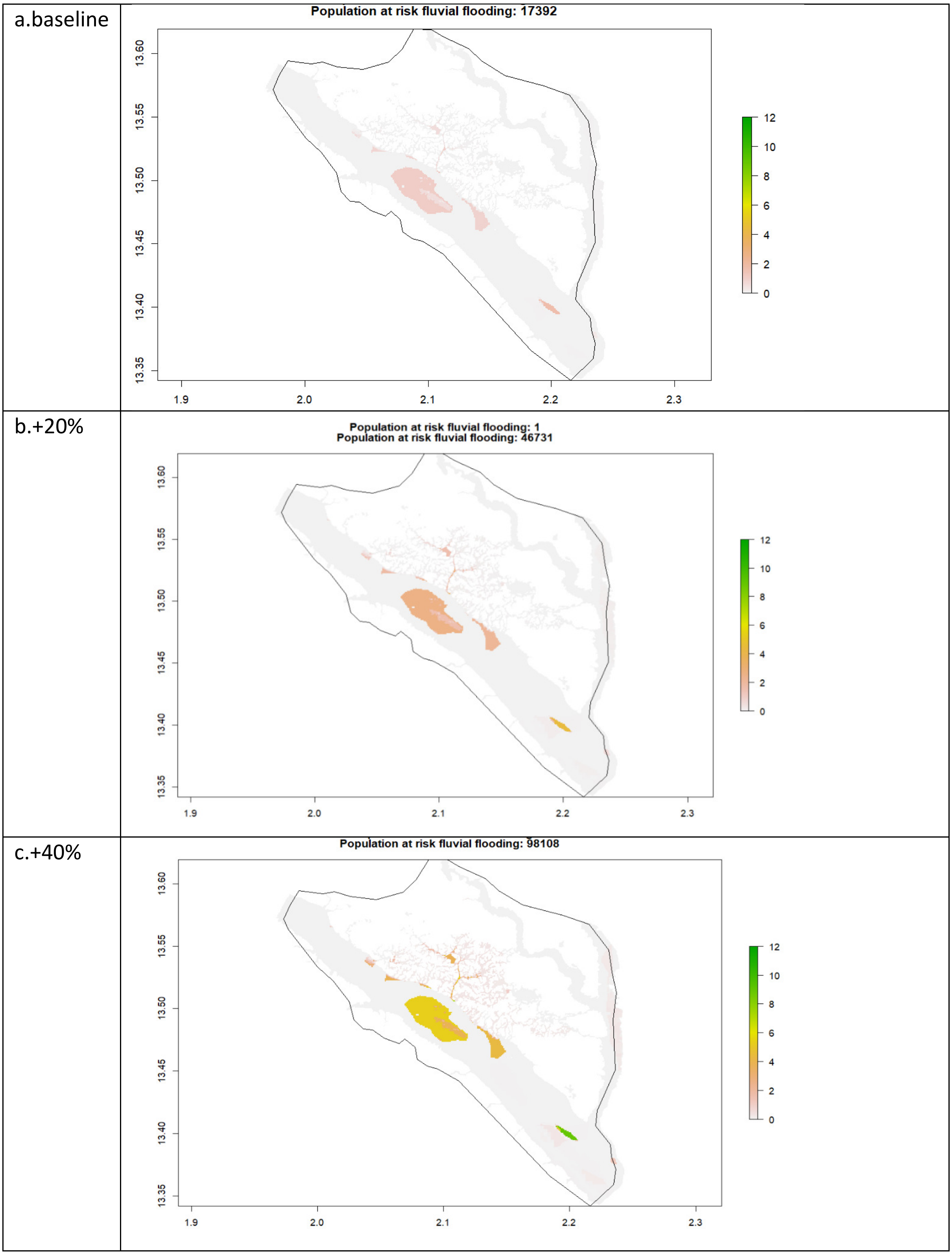

Figure 7: *Example visualisation of changing risk to people (expected annual people at risk) assuming linear growth in peak flows with range 20%-40% yielding EAP 17,322 increasing to [46,731-98,108].*

2. MITIGATING FOR CHANGING IMPACTS WITH AN INTEGRATED STRATEGY

The above analyses are focussed in areas of expected increases in flood risk, but do not exhibit particular tipping points, for which the expected losses increase suddenly and more rapidly. This suggests that whilst an adaptive approach is still useful, given uncertainties, there may be more to be gained by starting on multiple risk mitigations straightaway based on the principles of Integrated Flood Risk Management[7].

An integrated portfolio of flood risk management measures is more resilient because it takes a holistic and adaptive approach to flood risk, considering not just physical protection but also social, economic, and environmental factors. It provides a more comprehensive and sustainable solution to mitigate the impacts of flooding. There is evidence for this (Sayers et al., 2018) where different future mitigation strategies were tested for the UK. These included an 'enhanced whole system' (EWS) approach which was found to offset 10% greater EAD by the future epoch (2080) over continuing current levels of adaptation. This will vary from country to country but represents a significant reduction in damage to property and harm to people. All strategies retain a residual risk, but this is reduced more by the integrated approach. Defences were identified as the measure contributing the most to risk reduction, but catchment management and Property Flood Resilience were highlighted as significant contributions. This reflects their ability to mitigate the more frequent flood events, and they are often much more rapid to deploy than large schemes.

This suggests there is no time to lose and to maximise benefits we should get started with beneficial schemes from day zero. Whilst an adaptation pathway approach in flood risk management scheme appraisal recognizes the dynamic nature of climate change (Defra, 2020) and the need for flexible, long-term strategies that can respond to evolving conditions and uncertainties, it is argued a key message should be to start straightaway with a mixed flexible approach.

This can be prioritised in regions where flood risk is increasing the most, and the best adaptation pathway is likely to be an integrated portfolio (Sayers et al., 2018), combining a variety of approaches beyond traditional defences, such as early warning systems, land use planning, floodplain management, and sustainable drainage systems. This diversity allows for a multifaceted response to flood risk, but it needs to be targeted so every measure counts. There is also the argument that relying solely on traditional defences can create a single point of failure, sometimes placing the entire system is at risk, whereas a carefully planned integrated approach reduces this dependency on a single strategy. In addition, different studies have identified that Nature based Solutions (NbS) solutions can provide increasing levels of flood storage with increased flows if designed carefully (Hankin et al., 2021), as opposed to a defence, which once overtopped does not provide further protection. Therefore, the next section explores approaches at the strategic, national scale helping explore trade-offs between different combinations of risk management measures.

3. INTEGRATED FLOOD RISK MANAGEMENT AND TRADE-OFFS

Perhaps the best advice for greater resilience is to make a mixed / integrated FRM response and explore trade-offs giving similar risk-reduction but seek greater co-benefits. These may include societal[8] and environmental benefits which are often included as a lesser 'add-on', such as for example

[7] http://www.aidforum.org/topics/water-sanitation/integrated-flood-management-ifm-a-new-approach-to-flood-management/
[8] Nature-based Solutions can generate 20 million new jobs, but "just transition" policies needed (unep.org)

the 20% weighting of the OM4 environmental score on the partnership funding calculator in England[9]. There are more systematic approaches to assessing these multiple criteria using natural capital accounting, but the focus of this paper remains on appraisal and the key metrics of EAD and EAP.

Our approach to exploring trade-offs provides many more alternatives spatially than traditional Multi-Criteria-Analysis. It uses a 4 step process, which we have used in different countries:

1) Conceptualisation
2) Mapping potential areas (for IFRM) based on hazard, population and risk data (Figure 8)
3) Adjustment to risk calculation
4) Re-run probabilistic calculation to permit estimate of risk-reduction

This approach has been applied to four categories of FRM:

1) Traditional defences / embankments / dykes
2) Flood Early Warning Systems (EWS)
3) Property Flood Resilience
4) Nature based Solutions.

The spatial zones where each of these are mapped (step 2) look like the zones in Figure 8, and have been mined from different intersections of population, hazard and depth of flooding grids. This leans on techniques developed for the EA Potential Areas for Working with Natural Processes (Hankin et al., 2018).

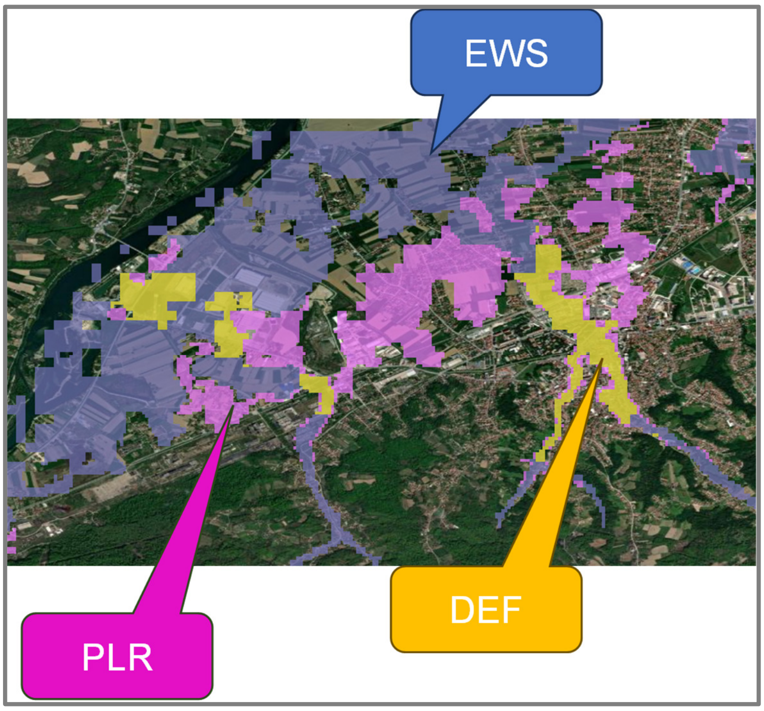

Figure 8: *Schematic to illustrate IFRM zones based on risk data*

[9] https://www.gov.uk/government/publications/partnership-funding-calculator-2020-for-fcerm-grant-in-aid-gia

After each of the risk-reductions have bene computed, the changes to the expected losses are stored against the spatial data, for example administrative boundaries. This is followed by spatial or tabular visualisation of the risks and risk-reductions across the introduction of IFRM.

By permitting spatial uptake or ambitions of different combinations of the measures in different places, this becomes a powerful 'what-if' tool to explore trade-offs between mixtures that give similar levels of mitigation. Figure 9 shows how this has been done in Excel for the Western Balkans resilience analysis for the World Bank[10].

Here two scenarios are shown, with the second (inset) providing a mixed IFRM solution that yields similar overall risk reduction to the more traditional and more expensive scenario 1. Both approaches mitigate against the expected increased losses with climate change for one of the 3 ensemble projections (RCP 8.5).

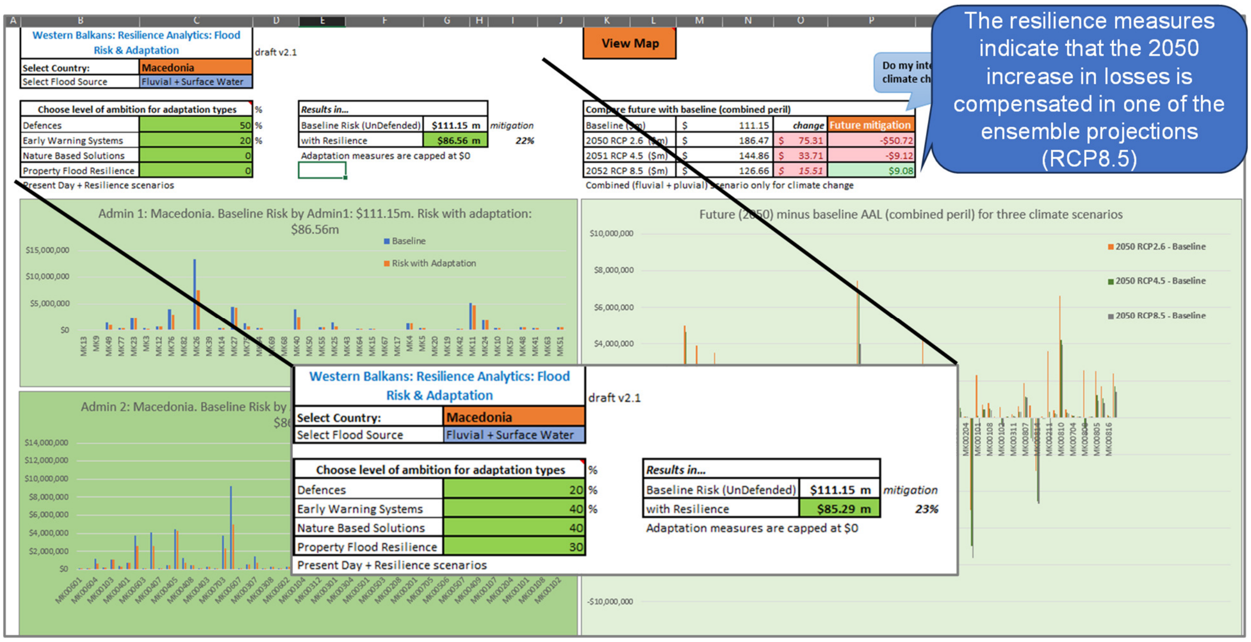

Figure 9. Trade-offs using the Resilience Analytics – Western Balkans

An advantage of this approach is that the full benefit of different portfolio options can be compared, with consideration of the residual or above design standard benefits of structural measures together with non-structural measures. Only considering the benefits up to the structural design standard constrains the economic appraisal and introduces bias towards structural measure portfolios which can deliver the target design standard of protection.

The same approach has been developed in Nepal, Indonesia, and Pakistan using a map-dashboard portal (Figure 10) called NIRA (Hankin et al., 2022).

[10] Acknowledgments also to GEMS for use of exposure data created for this analysis.

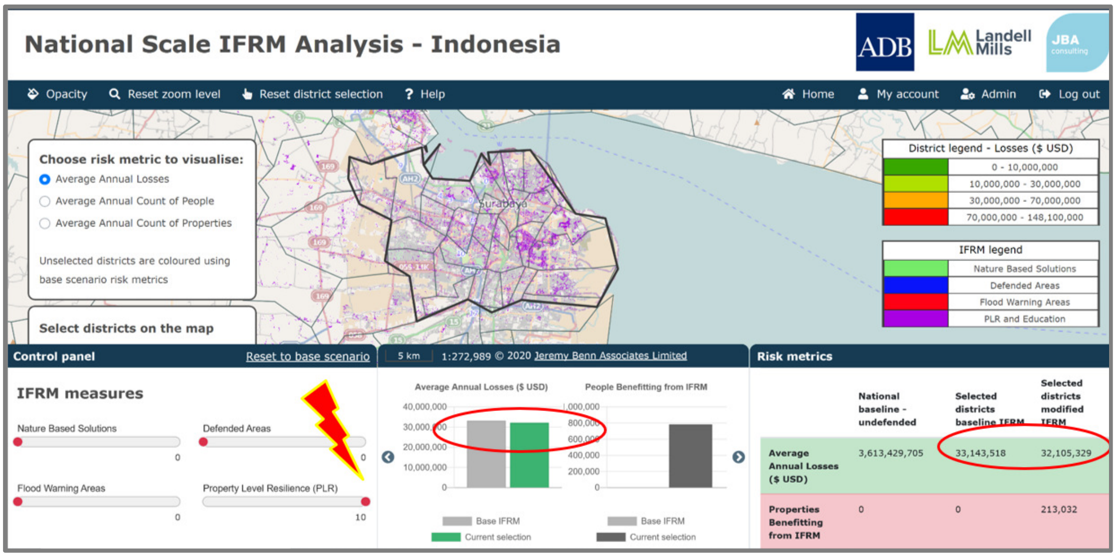

Figure 10: *Spatial Resilience Analytics using NIRA, developed for the Asian Development Bank (Hankin et al., 2022).*

The user can select a District (Admin 2) boundary, and as they move the slider for each IFRM measure, the benefit of adding the measures in the sub-district (Admin 3) are introduced. The approach was used to help the Indonesian government to objectively prioritise FRM schemes that were in the pipeline.

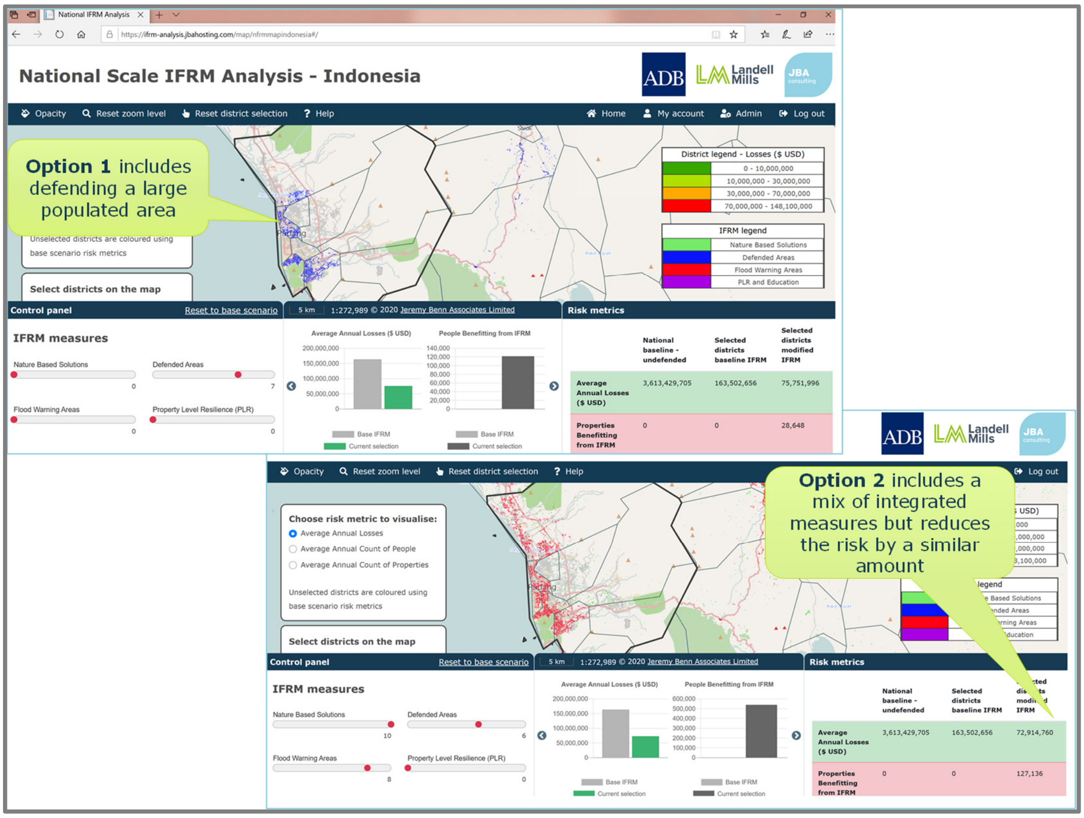

Figure 11: *Trade-off options using multiple metrics and levels of user-selected ambition for IFRM* (after Hankin et al., 2022).

The NIRA tool and framework captures economic flood risk reduction benefits and properties that benefit from risk reduction as an indicator of social benefits. The tool provides the framework for full appraisal of options and strategies which if desired could easily be extended for broader Multi-Criteria Analysis (MCA). For example, ecosystem service benefits could be included in the economic indicators, effects and benefits on social, utility and transport infrastructure could be captured, as well as the typical effect on aspects of the environment. The system allows for future change in economic activity and development, but care would need to be made in the qualitative MCA scoring and weighting as current societal values may not reflect future values.

4. SUMMARY AND CONCLUSIONS

This paper highlights the large uncertainties introduced in the appraisal of flood risk, and how for sample property and population data, a probably shift approach can be used to inform expected changes in these metrics. Two anonymised sample datasets are used to highlight very large changes to future risk, which make a huge difference in benefit-cost analysis. This implies we should be implementing risk reduction measures as soon as possible across multiple fronts that address different aspects of risk to people, property and livelihoods. This includes low-regrets property flood resilience measures to mitigate frequent shallow flooding, nature-based solutions with increasing ambition to tackle small to medium floods with small to medium frequency, and EWS and defences to bolster the resilience of urban infrastructure and denser populations. Different interactive tools have been developed to help navigate the possible trade-offs in IFRM, allowing a range of ambitions for each individual measure and in combinations. These can help steer or prioritise investment decisions or provide heat-maps of where more detailed modelling could be undertaken.

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