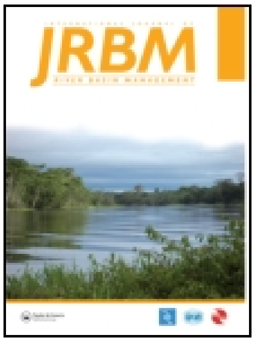

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Research paper

Aggregating spatially explicit criteria: avoiding spatial compensation

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ABSTRACT

Since the shift from safety-oriented planning towards risk-based flood management planning, both hydrology/hydraulic research as well as operations research have made remarkable progress. Unfortunately, in the transfer of information between both areas of expertise, valuable spatial information is being lost, which may lead to flawed decision-making. Spatial aggregation of positive or negative criteria score across cells as is customary holds a major pitfall: spatial compensation at the river basin scale. If one cell's benefits outweigh another cell's detriments, these detriments are lost in the spatial aggregation process. However, not all variables are commensurable. A decision-maker might reasonably object to an alternative that generates additional damage, even if they are amply compensated elsewhere. Current aggregation procedures have more of a tendency to veil these problems then to deal with them. Moreover, valuable information defined as spatial equity is also often lost in the decision matrix. In this paper, classical criteria are changed and new criteria are selected to inhibit the abundant spatial compensation, add the variable of spatial equity and provide decision-makers with non-ensconced and therefore more accurate results. The shortcomings and error-proneness of the established frugal summation procedures are outlined by intuitive simplified examples. These examples also serve to illustrate and test the logical performance of the proposed methodology. To test their applicability, they are used in an actual test case, selected for the problem's intricacy.

Keywords: Spatial compensation; spatial equity; flood management

1 Introduction

For a considerable number of basins in Germany (Petrow and Merz 2009, Bormann *et al.* 2011) and worldwide (Petrow and Merz 2009, Bormann *et al.* 2011), flood risk is rising. If not caused by flood trends than definitely by flood induced damages which are increasing, either caused by more detailed damage assessment, urban sprawl, river regulation, climate change or other factors (Black 1995, Cunderlik and Ouarda 2009, Schmocker-Fackel and Naef 2010, Eliot 2012). A lot of effort is being invested in meteorological, hydrological and hydraulic disciplines in order to accurately dimension for this increase in flood risk.

In flood protection studies, because of their complexity, multiple criteria decision-making (MCDM) algorithms are often used (Fernández and Lutz 2010). Different criteria are calculated for selected alternatives and summarized in the decision matrix. According to the decision-maker's preferences for different criteria, an algorithm can then prioritize the alternatives. One of the main criteria upon which decisions in flood protection are based is the reduced flood risk, quantified by changes in expected annual damage (Oliveri and Santoro 2000, Kelman and Spence 2004, Jonkman *et al.* 2008). It can be expressed as the difference of the integral of total damage ex ante for all probable events and can incorporate both primary damage and secondary damage (de Loë and Wojtanowski 2001, Dutta *et al.* 2003, Kelman and Spence 2004). At this side of the analysis chain, in operations research, decision support and optimization, the economical sciences have likewise established a substantial amount of algorithms (Figueira *et al.* 2005). Unfortunately, despite advanced geographical information systems (GISs), in coupling spatial data to decision algorithms, important information is lost, ensuing faulty decision-making.

Since criteria are commonly aggregated over the study area, GIS is often used to summarize the necessary data in order to calculate the criteria or target compliances (van der Sande *et al.* 2003, Vinet 2008). However, in doing so, the spatial component of the data is lost. Therefore, this clustering entails the possible occurrence of spatial compensation. Spatial compensation is a

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local deterioration that goes unnoticed because it is compensated by an improvement in another spatial location (or vice versa). See for instance Figure 6 in Evers *et al*. (2012), where the difference in damage between the simulated alternative and the current situation is described by the flooded area: 318,810 m^2 and 372,894 m^2. The simulated alternative seems to be effective: in over 5.4 ha inundation is avoided. But what if, in the flooded 31 ha, new areas are inundated that were previously not affected? In extreme cases, an alternative might lead to entire areas or even settlements being inundated without this event showing up in the decision matrix, if only the amelioration by this alternative in another location is high enough to compensate such an aggravation. Part of the scientific community has recognized this problem and reacted in two ways: with a classical and/or a graphical response.

The classical response to this problem is to add more criteria to the multi-criteria decision matrix. Indeed, spatially differentiating criteria give the appearance of solving the problem of spatial compensation. For instance, if the amelioration occurs in industrial areas and the deterioration in municipal areas, adding a criterion ‘affected people’ can in some way take the differentiation in the aforementioned losses and gains into account. However, it should be clear that the underlying problem of spatial compensation is not solved by adding more criteria, just masked. For if spatial compensation occurs within one, however, specific, criterion it is not incorporated within the decision matrix. In the aforementioned example, spatial compensation within municipal areas still remains hidden.

The graphical response to the spatial compensation problem is the presentation of flood hazard and/or damage risk maps to the decision-maker(s) in which the spatial shifts in hazard or risk can be recognized. In the cited example of Evers *et al*. (2012), the spatial differences in inundation are additionally provided as images to the decision-maker(s). An image can convey more information than words, so maps can be a valuable (additional) source of information and will probably become even more relevant in the future. However, maps remain a very ‘rough’ source of information: judgements and evaluations of alternatives based on visual information presented in these maps rely on the premise that decision-maker(s) and/or stakeholder(s) can recognize and interpret all the relevant information contained. So, although risk maps can provide the decision-maker(s) with valuable additional information, shifting the responsibility for detecting and/or avoiding spatial compensation from the scientist to the decision-makers(s) cannot be the optimal solution. Especially in flood risk management, where often a multitude of possible alternative solutions have to be evaluated for a multitude of possible floods with different return periods – possibly even for different climatic and/or societal scenarios – the sheer amount of data to be processed implies a certain amount of data aggregation. These aggregation procedures should avoid spatial compensation.

Another aspect that often goes unnoticed is spatial equity. Because of the classical aggregation procedure, the decision-maker has no knowledge of the spatial extent underlying summarized criteria like economic damage or affected persons. The expected annual damage might be caused by a spatially very confined event with a high amount of damage per unit area or a very wide scaled event with a very low amount of damage per unit area. The spatial distribution of benefits and burdens has little or no influence in the aggregation procedures as performed today. This causes decisions to be made almost independent of equity. The visualization of risk maps for all stakeholders can be very valuable, providing that the decision-maker(s) are able to objectively identify, assimilate and interpret all important criteria; which – unfortunately – means limiting the number of alternatives, return periods and/or scenarios.

Fortunately, both the problem of spatial compensation and loss of spatial equity can effectively be resolved. In this paper a simplified numerical example will be used to demonstrate both problems and their detrimental effects on decision-making. The simplicity and effectiveness of the proposed solutions can also be made clear using this hypothetical example. Next, both the danger of and solution for spatial compensation will be demonstrated using a real case study. Note that the decision algorithms and decision-making set-up (group decision-making, stakeholder involvement, participatory approaches, etc.) are deliberately kept simple in order to focus on the problem of spatial compensation. The problem of spatial compensation exists in all constellations since the central idea is that information delivered to the decision-makers/stakeholders/participants can be (and often is) flawed.

2 Methodology for avoiding spatial compensation

To solve the problem of spatial compensation, all masking criteria are excluded from a numerical example for which spatial compensation inhibiting solutions can then be presented. This has the advantage of a simplified example upon which algorithms can be tested and which is nevertheless clear enough to be interpreted by common sense. Therefore, please notice that the problem sketched here is intentionally greatly simplified and serves to illustrate spatial compensation that could occur within the smallest unit differentiable by all additionally addable criteria.

2.1 *Outline of the simplified example*

Imagine the following situation: a river passes two locations and its yearly flood events cause damage in both sites. The river flows from south to north (Figure 1). The location of the caused damage is depicted as circles. The numbers inside these circles indicate the amount of damage caused.

As is clear from Figure 1, the location to the south suffers most damage. To reduce the yearly damage, two different solutions are proposed: a flood canal (alternatives 1 and 2) and an

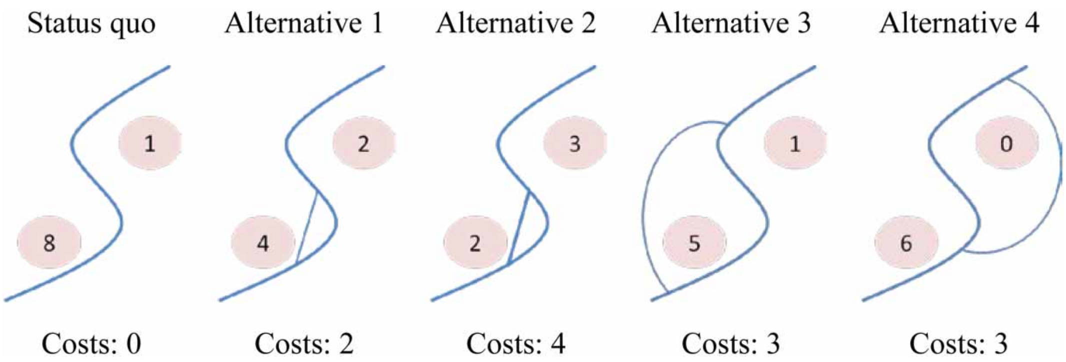


Figure 1 Sketch of spatially distributed damages indicated in circles, simplified solution scenarios and their effects.

artificial oxbow (alternatives 3 and 4). In both cases, two slightly varying solutions are to be analysed.

Alternative 1: small flood canal.

> The damage in the southern location is halved because of this bypass. Unfortunately, because of the increased discharge, the northern location suffers a slight increase in damage. The costs for this canal are low: 2 units: leading to a net damage reduction of 3 units.

Alternative 2: broad flood canal.

> The damage in the southern location is vastly reduced. Unfortunately, because of the increased discharge, the northern location suffers an even higher increase in damage. The costs for this canal are high: 4 units. All in all the net damage reduction is 4 units.

Alternative 3: western oxbow.

> The damage in the southern location is reduced minimally, but the northern location remains free of additional damage. The costs for this canal are medium: 3 units. All in all the net damage reduction is 3 units.

Alternative 4: eastern oxbow.

> The damage in the southern location is reduced even less, but now the northern location has something to gain from this alternative: its damages disappear entirely. The costs for this canal are medium: 3 units. All in all the net damage reduction is 3 units.

It is clear that although economically preferred, solutions 1 and 2 are politically unacceptable due to the increase in damage in the northern location. The solutions 3 and 4 can be differentiated based on the equity criteria. Unfortunately, disregarding the spatial differentiation between alternatives 1 and 4 leads to a clear preference for alternative 1 in all MCDM algorithms, based on the decision matrix in Table 1.

This illustrates why the condition assessment phase, with regard to the choice phase, has to take spatiality into account. If the aggregation is faulty and spatiality is ignored, the efficiency of the decision algorithms in the choice phase becomes irrelevant in light of the larger mistakes already made. Therefore, the challenge in spatial decision-making is trying to find an aggregation procedure that disallows spatial compensation.

Table 1 Calculation example decision matrix without taking spatial compensation into account

	Costs	Benefits
SQ	0	0
Alternative 1	2	3
Alternative 2	4	4
Alternative 3	3	3
Alternative 4	3	3

2.2 *Different aggregation procedures*

The following aggregation procedures can be discriminated:

(a) Classical aggregation in cost and damage
  In ‘classical’ flood inundation studies, the aggregation procedure is a simple summation of cost and damage (or other criteria) over the entire river basin.

(b) Area-wise aggregation of damages
  One of the simplest ways to reduce or even eliminate spatial compensation is to attribute each individual area a criterion. This ensures that benefits in one area do not compensate losses in another area.

(c) Differentiation of damage increase and damage decrease
  Another elegant way of avoiding spatial compensation is simply not to sum increases and decreases in damage, but to keep them apart as single criteria.

(d) Total damage and damage in- or decreasing instances
  Counting the number of instances (or raster cells) in which damage increases and subtracting them from the number of instances in which damage decreases incorporates a wholly new spatial element as one criterion. The idea is that beneficial effects should be distributed as evenly as possible and detrimental effects should spatially be contained as much possible.

(e) A combination of the two latter procedures
  Keeping the increase and decrease of damage and instances separated.

The decision matrices of the aggregation procedures can be calculated as given in Table 2.

Table 2 Five aggregation procedures and the resulting decision matrices

		a	b		c		d		e			
	Costs	ΣDmg	South	North	Dmg↓	Dmg↑	ΣDmg	#	Dmg↓	Dmg↑	#↓	#↑
SQ	0	9	8	1	0	0	9	0	0	0	0	0
Alternative 1	2	6	4	2	3	1	6	0	3	1	1	1
Alternative 2	4	5	2	3	4	2	5	1	4	2	1	1
Alternative 3	3	6	5	1	3	0	6	1	3	0	1	0
Alternative 4	3	6	6	0	3	0	6	2	3	0	2	0

Notes: 'ΣDmg' stands for the summarization; 'Dmg↓' and 'Dmg↑' for the decrease and increase of damages, respectively; '#↓' and '#↑' for the number of locations where these changes occur; and '#' equals '#↑' – '#↓'.

2.3 *Evaluating the decision matrix: different MCDM algorithms*

Numerous analytical techniques for handling multiple criteria problems have been developed and deployed (Figueira *et al.* 2005). Two very simple MCDM algorithms are compromise programming (CP) (Zeleny 1973, Duckstein and Opricovic 1980, Opricovic 2009) and TOPSIS (Technique for Order Preference by Similarity to Ideal Solution) (Hwang and Yoon 1981, Simonovic and Verma 2008). These are two well-established methods, frequently used in water management issues (Hajkowicz and Collins 2007). CP is based on measuring the distance to a referential, infeasible and ideal solution. For each criterion j, the alternatives i are normalized into commensurable, unit-less distance metrics to this ideal point. The optimal solution is then obtained by minimizing the weighted distance (L_i).

$$L_i = \left[\sum_{j=1}^{n} w_j^p \left(\frac{x_j^+ - x_{ij}}{x_j^+ - x_j^-} \right)^p \right]^{1/p},$$

where x_j^+ is the positive ideal value of the corresponding criterion and x_j^- is the negative (worst) ideal value and w_j is the relative weight attributed to each criterion. For the compensation factor p, the value of 2 will be used. TOPSIS analyses not only the distance towards the positive ideal situation ($D_i{}^+$), but also the distance towards the most negative situation ($D_i{}^-$) and calculates the relative closeness to the ideal situation $\bar{C}_i$ after vector normalization and weighing (Srdjevic *et al.* 2004, Liu *et al.* 2006).

$$\bar{C}_i = \frac{D_i^-}{D_i^+ + D_i^-} \text{ with } D_i^+ = \sqrt{\sum_{j=1}^{n} w_j^2 (x_{ij} - x_j^+)^2}$$

$$\text{and } D_i^- = \sqrt{\sum_{j=1}^{n} w_j^2 (x_{ij} - x_j^-)^2}.$$

For comparability reasons, a weight of 20% for the costs will be used for all aggregation procedures and the remaining weight will equally be distributed over the other criteria. Also, if we reverse the sorting order of the CP results using $L_i^* = 1 - L_i$, the best results of both CP and TOPSIS are the alternatives nearest to 1 and the worst nearest to 0.

Table 2 gives the results obtained by:

(a) Classical aggregation in cost and damage

As expected, both CP and TOPSIS would classify alternative 1 as the best (the best solution for CP is the one nearest to the utopic solution and the best solution of TOPSIS is the one farthest from the negative ideal situation (NIS)). Based on this classical summation, no differentiation is possible between alternatives 3 and 4.

(b) Area-wise aggregation of damages

This clearly produces a prioritization almost fully according to standard perceptions of the simplified example. Spatiality is incorporated 'sensu-stricto'. However, this might become very labour-intensive in areas with (for instance) a large number of communities and is considered as impractical. Nevertheless, these priority scores can be used exemplary for the other aggregation procedures, especially the slightly more advanced TOPSIS prioritization.

(c) Differentiation of damage increase and damage decrease

Only two criteria (and costs) are needed: this makes it a very easy aggregation procedure. Alternatives 1 and 2 are effectively discarded since spatial compensation cannot occur. Unfortunately, this procedure does not discriminate between alternatives 3 and 4 since the spatial equity cannot be incorporated. The spatial equity is another element that is often lost in the classic summation.

(d) Total damage and damage in- or decreasing instances

This procedure still allows a certain amount of compensation in the criterion 'total damage', but introduces a spatially very prominent criterion: the number of instances. This criterion includes spatial equity and alleviates spatial compensation.

(e) A combination of the two latter procedures

The best of both c and d: spatial compensation is very efficiently rendered impossible and spatial equity is incorporated. Notice that the weights of the TOPSIS algorithm are almost identical with targeted 'sensu-stricto' analysis.

Table 3 Resulting CP and TOPSIS priority scores using different aggregation procedures for the numerical example

	a		b		c		d		e	
	CP	TOPSIS	CP	TOPSIS	CP	TOPSIS	CP	TOPSIS	CP	TOPSIS
SQ	0.2	0.37	0.56	0.52	0.6	0.61	0.2	0.26	0.5	0.57
Alternative 1	**0.9**	**0.67**	0.73	0.44	0.82	0.86	0.52	0.22	0.66	0.45
Alternative 2	0.8	0.62	0.4	0.37	0.4	0.82	0.4	0.22	0.45	0.34
Alternative 3	0.84	0.59	**0.74**	0.57	**0.86**	**0.92**	0.76	0.49	0.82	0.67
Alternative 4	0.84	0.59	0.71	**0.66**	**0.86**	**0.92**	**0.86**	**0.78**	**0.87**	**0.74**

Note: Numbers in bold represent the 'best' solution.

2.4 *Effects of a shift in weights*

One might argue that a lot depends on the decision-maker's valuation of costs over damage and that the 20% used to calculate. Table 3 only represents part of the range of possible outcomes. In order to be as general as possible, instead of using an exemplary percentage and calculating one number, the entire range of possible outcomes can be returned when a second dimension is used (Figure 2) characterizing the degree of priorities of costs.

In all aggregation procedures it can be seen that if the weight of the criterion cost rises over 80%, the status quo (SQ) alternative gains the highest priority. Also, as elegant and simple as the aggregation in damage increase and damage decrease might be, this aggregation procedure does not discriminate a lot between the different alternatives (as in the case of SQ, alternative 3 is equal to alternative 4). This means that although spatial compensation is effectively avoided, a piece of the puzzle is still missing. The aggregation in damage increase and damage decrease does not evaluate the spatial distribution of costs and/or benefits. Aggregation procedure 'd' on the other hand does discriminate intensely between alternatives 1 and 4, but less between 2 and 3, demonstrating a very high emphasis on spatial equity to the point of allowing a slight amount of

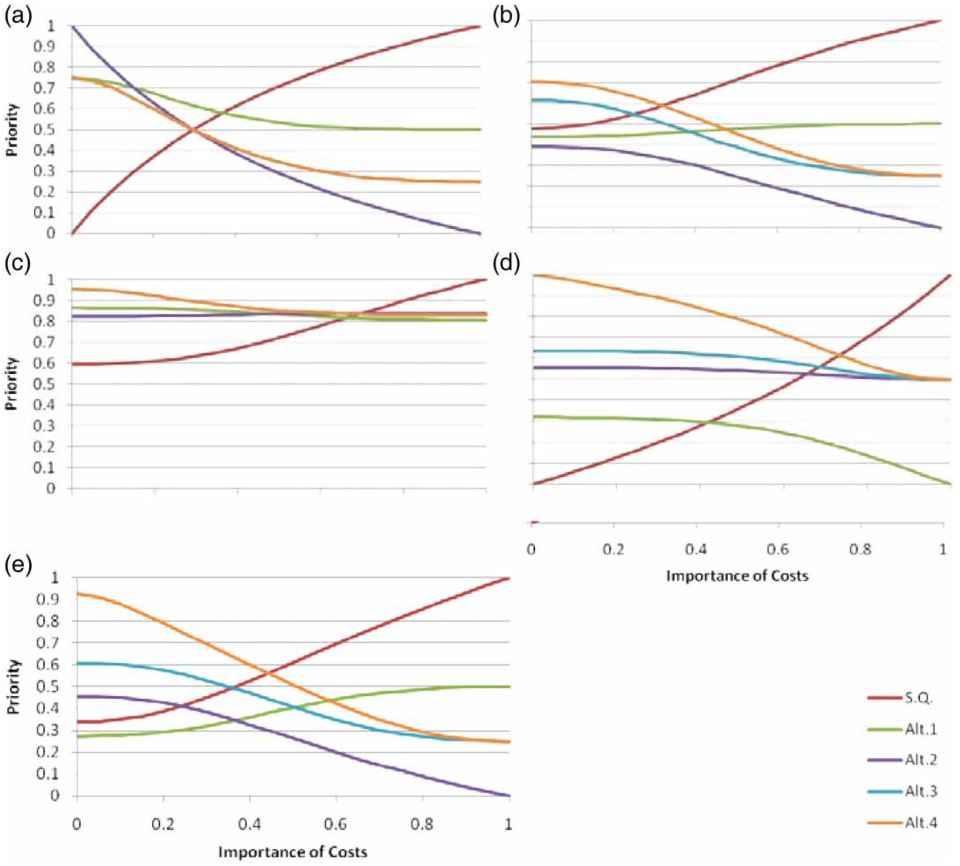


Figure 2 Priority shifts of the costs/damages TOPSIS analysis caused by varying the relative importance of the cost criterion. Aggregation procedure 'a' is the classical summarization of damages; 'b' is the area-wise aggregation of damages; 'c' is the differentiation in damage increase and damage decrease; 'd' is the summarization of damages and damage increasing or decreasing instances; and 'e' is the combination of 'c' and damage increasing or decreasing instances.

spatial compensation. Aggregation procedure ‘e’ demonstrates the benefits of ‘c’ and ‘d’ as proven by its similar shape as the ‘sensu-stricto’ solution ‘b’ and even achieves a slight increase in differentiation between all alternatives. Therefore, aggregation procedure ‘e’, a combination of the differentiation in damage increase and damage decrease with a count of the damage in- or decreasing instances, proves to be the better method to aggregate (damage) data with respect to spatiality.

3 Application: comparison of aggregation procedures in a case study

The goals of this application are to show that:

- (i) Spatial compensation can occur in real cases.
- (ii) Spatial compensation may hide important information
- (iii) Ignoring spatial compensation might lead to incorrect decisions.
- (iv) Spatial equity is important information and can be integrated in the analysis.
- (v) More demarcations gradually reduce spatial compensation; if compensation across these demarcations is not allowed.
- (vi) That spatial compensation can be eliminated.
- (vii) If spatial compensation is eliminated, demarcations do not influence the results.

3.1 *Study area*

The methodology is applied to the flood-prone catchment of the river Unstrut in the central part of Germany. The almost 6400 km^2 large catchment displays a variable topography covering almost the entire Thuringia basin and parts of the Thuringia Forest ranging from 104 to 982 m in altitude (NHN). At present, the technical flood retention system within this river basin consists of two larger and a few smaller reservoirs, a flood channel and a flood polder system with five polders (SQ). In total the flood retention system has a volume of nearly 100 10^6 m^3. Local planning authorities suggested a set of flood control measures, varying from the optimization of the existing polders (alternative 1), an increase of retention time within polders by additional check dams to the creation of new polders (alternative 2), to an alteration of the polder inlet structures (alternative 3) and different types of inlet regulations (controlled and uncontrolled flooding) (Alternatives 5 and 6). From a long series of runoff simulated on a daily basis by coupling a stochastic rainfall generator and a deterministic hydrological model (Mostert and Junier 2009, Scott and Gemmell Campbell 2012), a series of hydrological loads with return periods of 1:25 – 1:1000 years were selected. After level pool routing (Hundecha *et al.* 2008, 2009) in the two larger reservoirs the propagation of flood waves along the river course was simulated with a coupled 1-D/2-D hydraulic model by the Institute of Hydraulic Engineering, RWTH Aachen (Kamrath *et al*. 2006). All six system states were thus evaluated. From the resulting inundation rasters, the expected damage was calculated for every cell using an automated GIS-based damage expectancy value estimation algorithm (Nijssen *et al.* 2009).

In order to conclusively prove that spatial compensation exists (and can be avoided), the study area is spatially divided into different levels across which compensation is to be avoided. Aggregation procedure ‘b’ would in theory be based on each individual raster cell, which effectively inhibits spatial compensation. However, this would be unpractical as well as unrealistic since decision levels are seldom on a raster level. A classical aggregation and decision-making level at a lower spatial resolution than the inundation cells is the community: 66 are exposed to varying degrees of inundation risks. A spatial resolution level between the communities and the entire area is defined by delineating six different sub-basins. Aggregating the entire damage prone area would represent the third and final spatial resolution level (Figure 3).

3.2 *The problem of spatial compensation in numbers*

In most cases, the evaluated water management measures are beneficial: flood waters are held back in polder areas, dikes keep flood waters away from vulnerable areas, etc. In risk assessment, however, very extreme events also have to be evaluated and this is where flood retention measures sometimes proved to be detrimental. For instance, a wave with a return period of 1:500 years (Figure 4).

Note that the orange areas shown in Figure 4 are mostly situated in the polder areas. However, especially during events with larger return periods, some areas that were not affected might become inundated: see the village of Leubingen in the inset. For this event, the global reduction of expected damage outside of this city monetary outweighs the expected damage inside. Without differentiation in damage reduction and damage increase, the modelled measures would prove an unencumbered net gain.

This is of course a visually striking example, but experience has shown that smaller incidences of spatial compensation occur abundantly when modelling large basins. See for instance Table 4, which lists the expected damage of a smaller wave with a return period of 1:100 years. To numerically measure the effects of spatial compensation, all five aggregation procedures were applied on the expected damage raster. In accordance with the methodology, the first aggregation performs a summation over the river basin (Table 4). The expected annual costs are a combination of recurring (the integral of total costs ex ante for all probable events and maintenance costs) and non-recurring events (construction, alteration and renovation), recalculated to a yearly basis. Using the integral of total damages, ex ante for all probable events would hide individual effects of spatial compensation since different spatial compensation patterns occur during the aggregation of all of the 30 simulated events with return periods between 1:25 and 1:1000 years. Therefore, the expected damage for a single return period is given in Table 4, in this case 1:100 years. Take note that both columns (annual expected costs and expected damages for one return period) cannot simply be

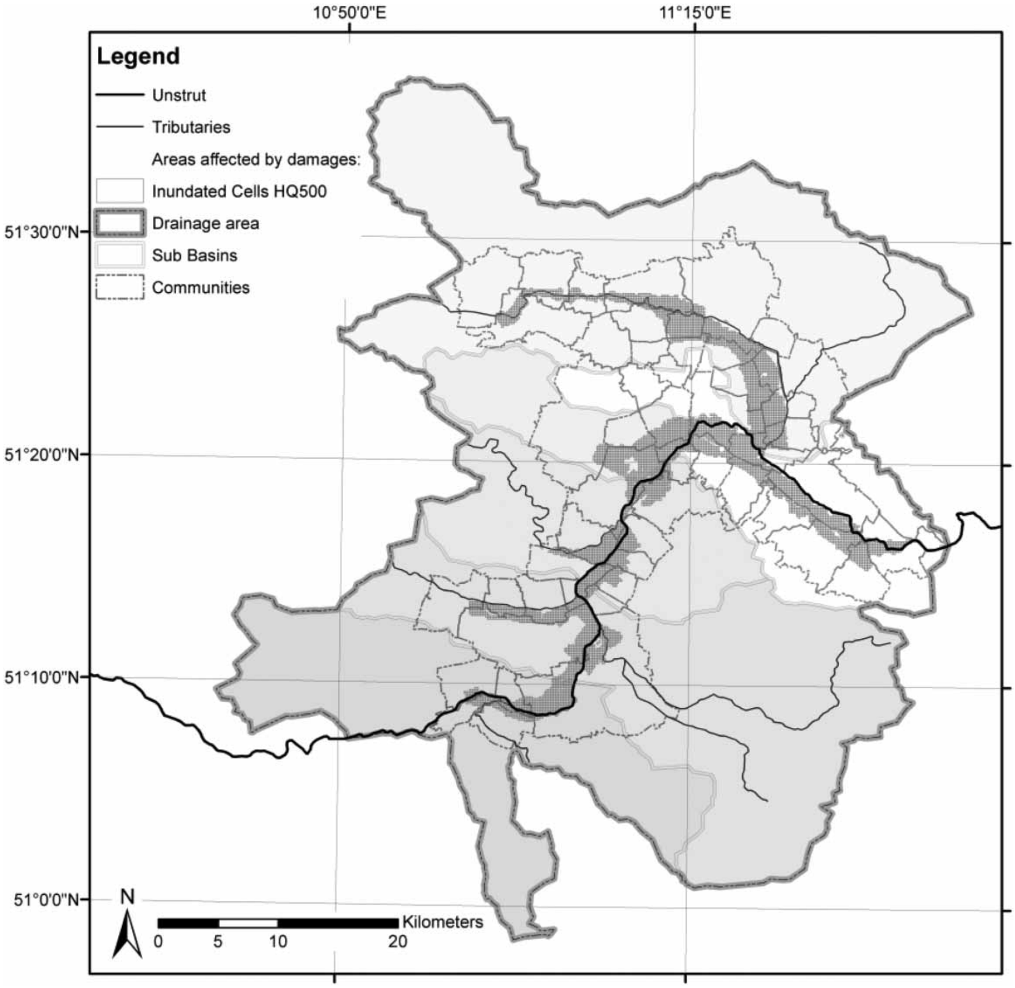


Figure 3 Three different spatial levels in damage accumulation: communities, sub-basins and the total area.

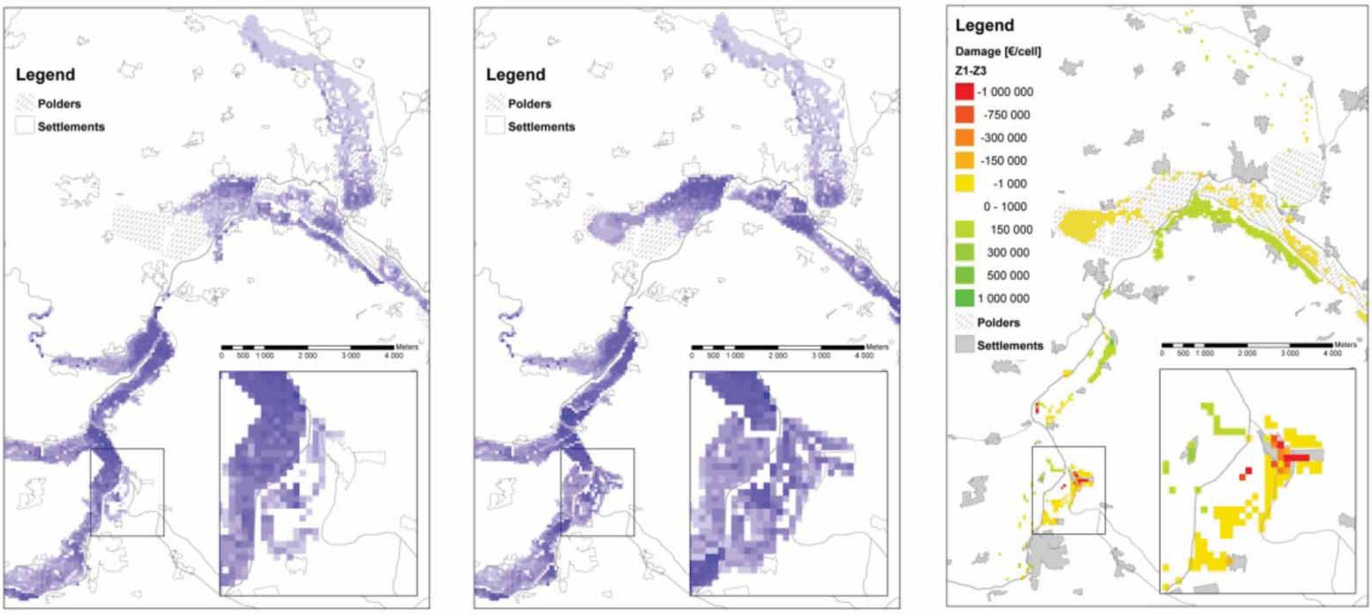


Figure 4 Inundation simulation for a return period of 1:500 years. On the left the current situation, in the middle the scenario with an activation of multiple polders and on the right the difference between expected damages of both simulations. The inset shows an enlargement of the village of Leubingen.

Table 4 Classical aggregation ‘a’ of costs (construction, maintenance and including damages in polder areas) and damages over the entire basin for the wave with a return period of 1:100 years

	Costs (€/a)	Total expected damage (€)
SQ	0	28,450,200
Alternative 1	160,069	29,586,700
Alternative 2	256,559	80,97,000
Alternative 3	441,111	67,86,200
Alternative 4	437,755	67,72,200
Alternative 5	460,875	68,50,900

Table 6 Aggregation strategy ‘c’ the wave with a return period of 1:50 years, where damage decrease and damage increase (compared to the SQ) are individually summarized, otherwise, the damage increase would almost cancel the damages decrease

	Costs (€/a)	Damage decrease (€)	Damage increase (€)
SQ	0	0	0
Alternative 1	160,069	1,291,750	746,500
Alternative 2	256,559	2,724,200	3,316,550
Alternative 3	441,111	2,920,650	3,350,700
Alternative 4	437,755	2,965,050	3,127,600
Alternative 5	460,875	2,972,600	3,343,350

arithmetically combined. Moreover, the criteria (cost and benefits) are deliberately kept simple to show the spatial compensation.

For the ‘area’ in aggregation procedure ‘b’, the 66 communities were selected since attributing each raster cell would have been computationally overly intensive (>30,000 ‘criteria’). Therefore, spatial compensation within a community remained possible by this aggregation. The aggregation procedure ‘c’ in Table 5, a differentiation between increasing expected damage and decreasing expected damage for every cell shows, in comparison with Table 4 the very real problem with classical aggregation:

As can be seen from Table 5, the different inundation preventing alternatives actually do increase the expected damage for about €4 million for this inundation. This means that this inundation contributes approximately €40,000 per year to the expected total annual damage estimation (integration over the total range of possible return periods is more correct, but obscures the spatial compensation issue at hand). This proves goals (i) and (iv) of the case study: that spatial compensation can occur in real life and be eliminated by the selection of correct criteria.

The second (ii) goal is to prove that the information, hidden by spatial compensation, might be relevant to the decision-maker. As the decrease in expected damage for the specific wave given in Table 5 is large enough, one might argue that the increase in estimated damage could be neglected. However, for other return periods, the spatial compensation might balance the decreases and increases; like for instance the wave in Table 6, which has a return period of only 1:50 years (based on the wave height, the return period based on the volume is almost 1:500 years, which is why the expected damage is higher than that given in Table 5. For more information about these issues please refer to Nijssen *et al.* 2009).

Table 5 Aggregation strategy ‘c’ for the wave with a return period of 1:100 years, where damage decrease and damage increase are individually summarized, thus preventing spatial compensation

	Costs (€/a)	Damage decrease (€)	Damage increase (€)
SQ	0	0	0
Alternative 1	160,069	−395,100	1,531,600
Alternative 2	256,559	−24,254,900	3,901,800
Alternative 3	441,111	−25,995,100	4,331,200
Alternative 4	437,755	−25,995,800	4,317,800
Alternative 5	460,875	−26,116,600	4,517,300

If the expected damages of Table 6 were simply summarized, the technical measures would seem to have almost no effect. This proves the second goal (ii).

Moreover, neither in Table 4 nor in Table 6, information about spatial equity is visible. In other words: is the expected damage increase/decrease related to an isolated instance of a very valuable area or is the area well distributed? Aggregation procedure ‘d’, which counts the number of cells where the expected damage increase and subtracts them from the number of cells where the expected damage decreases gives a very good indication thereof, adding two more columns or criteria to Table 4.

Table 7 gives effectively that the expected damage decrease occurs in less than half the number of cells compared to the expected damage increase; thus incorporating spatial equity

Table 7 Additional column from aggregation strategy ‘d’ for the wave with a return period of 1:100 years, where the number of cells of damage decrease is subtracted from the number of cells with damage increase

	Number of cells damage decreases (#)	Number of cells damage increases (#)	Number of cells changes in damage (decrease − increase)
SQ	0	0	0
Alternative 1	131	1070	−939
Alternative 2	354	971	−617
Alternative 3	447	957	−510
Alternative 4	452	969	−517
Alternative 5	563	1180	−617

Table 8 CP and TOPSIS results for all aggregation strategies for the wave with a return period of 1:100 years

	a		b		c		d		e	
	CP	TOPSIS	CP	TOPSIS	CP	TOPSIS	CP	TOPSIS	CP	TOPSIS
SQ	0.278	0.221	**0.441**	**0.817**	0.6	**0.847**	0.439	0.393	0.6	**0.536**
Alternative 1	0.176	0.147	0.296	0.613	0.542	0.626	**0.402**	**0.238**	**0.477**	0.375
Alternative 2	**0.935**	**0.857**	0.316	0.474	**0.638**	0.451	0.763	0.656	0.625	0.479
Alternative 3	0.817	0.798	0.218	0.227	0.449	0.162	0.635	0.628	0.493	0.455
Alternative 4	0.82	0.799	0.182	0.219	0.454	0.164	0.62	0.629	0.494	0.456
Alternative 5	0.82	0.799	0.158	0.198	0.4	0.153	0.599	0.616	0.4	0.455

Note: Numbers in bold represent the 'best' solution.

with one (aggregation procedure 'd') or two additional columns (aggregation procedure 'e').

Aggregation procedure 'e' combines the spatial compensation blockage of procedure 'c' (expected damage decrease/increase) with the spatial equity inclusion of procedure 'd' (number of inundated cells decrease/increase). Calculating the CP and TOPSIS values from all five procedures results given in Table 8, weights are handled analogous to the methodology and the simplified example.

In Table 8, it can be seen that for aggregation procedure 'a', summarizing the expected damage, the best solution is alternative 2. An evident solution based on Table 4. Both CP and TOPSIS are in perfect agreement. However, if the spatial compensation is reduced by disallowing compensation between communities, as in aggregation procedure 'b', the SQ seems the best. This is confirmed in procedures 'c and e' by the TOPSIS analysis. This proves goal number (iii): that spatial compensation can lead to faulty decision-making.

Since CP calculates the distance to the optimal solution and TOPSIS incorporates on top of this, the distance to the worst situation (NIS), thus adding NIS-criteria (as in 'c, d and e'), results can strongly differ between both procedures. This proves that the duality of the expected damage caused by the wave HQ100_2320 is being retained in the decision matrix by procedures 'c' and 'e' and a decision-maker now has a chance to weigh the increase in expected damage. This option was not available in analyses 'a' and 'b'. If the weight of the expected damage increase criterion is increased, the priority scores of the CP algorithm conform to the priority scores of the TOPSIS algorithm.

The trend break in procedure 'd' reflects in TOPSIS the strong difference between SQ, alternative 1 and the other alternatives, especially concerning the cost and damage, as in 'a'. Especially alternative 1, where the increase in expected damage is widespread (a high equity for expected damage increase) and the expected damage reduction is relatively limited (see Table 7), is ranked by procedure 'd' as the worse solution. This proves that spatial equity can be important and can be integrated in decision-making (goal iv). This is an important variable, especially in risk-based decision-making where local increases in expected damage for a certain return period are not completely eliminable.

Procedure 'e' is, as expected, intermediate between 'c' and 'd'. The similarity between 'e' and 'b' is not as strong as in the simplified example, because within the smallest demarcation for 'b' (communities), there nevertheless remains a possibility for spatial compensation.

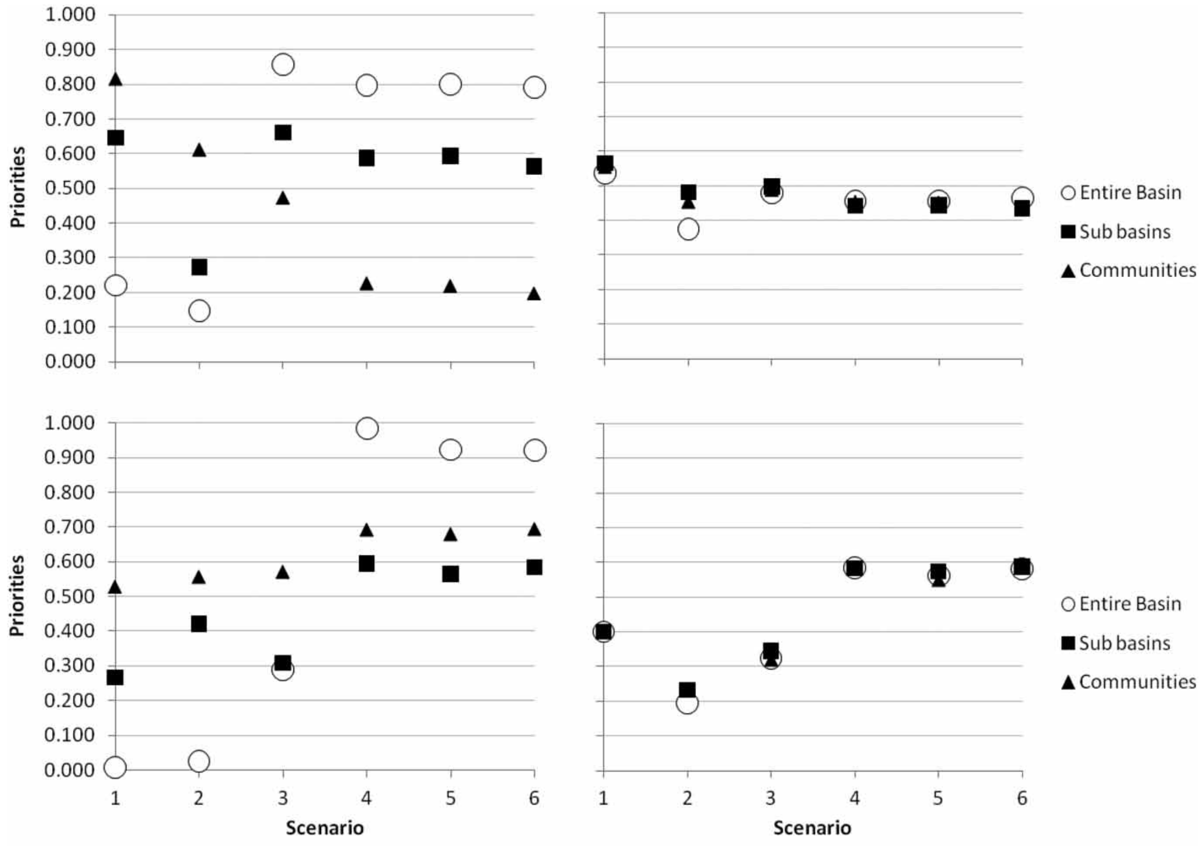
3.3 *Effects of resolution on spatial compensation*

If it is really the element of spatial compensation that distorts aggregation procedure 'a' and is avoided by aggregation procedure 'b', then lower resolution criteria in 'b' would have to give rise to intermediate priorities. This is tested by dividing the river basin not in 66 communities, but in six sub-basins; allowing spatial compensation within these sub-basins but not between the sub-basins. Aggregation procedures that disallow spatial compensation should result in the same priorities, independent of the considered resolution.

As can be seen from Figure 5, in aggregation procedure 'e' (a combination of the differentiation in expected damage increase and decrease with a count of the damage in- or decreasing instances) there is almost no difference anymore between the basin approach, the sub-basin approach or the individual communities approach. This means that, using the right aggregation procedure eliminates the effects of spatial resolution on the final outcome; proving goals (v) and (vii).

The same analysis was performed on 24 other inundation events, ranging from a return period of 25–1000 years and similar results were obtained, even when the expected damage was differentiated in polder, village or agricultural areas. Moreover, the analysis was also performed on the total number of endangered individuals (adults and children) and on the number of especially sensitive institutions (hospitals, retirement homes, etc.). Similar results were obtained. It is evident that, because of its simplicity, the methodology is also applicable for other criteria.

The following steps in the flood risk management analysis procedure are: integrating over all return periods in order to find the annual expected damage, annual expected number of endangered individuals and sensitive institutions and combining all these different criteria in an MCDM algorithm. Since the proposed procedures change only the number of criteria, their



Aggregation strategy 'b': using the entire basin, 6 sub basins or 66 communities as aggregation resolutions.

Aggregation strategy 'e': disallowing spatial compensation.

Figure 5 Effects of differences in resolution using the 'senso-stricto' aggregation strategy 'b' and the aggregation strategy 'e', priority scores of the wave with a return period of 1:50 years calculated with TOPSIS for the top row and priority scores of the wave with a return period of 1:100 years calculated with CP for the bottom row.

combination can evidently be performed using the traditional MCDM methods with the additional advantage of being able to fine-tune the importance of a criterion reduction against its spatial equity and a possible penalization of a criterion increase.

4 Discussion

In order to avoid or alleviate extreme wave crests, flood management systems move or store a certain amount of water temporarily in reservoirs, retention basins, polders, riparian wetlands, rainwater harvesting systems or others. Therefore, the classical solution often entails a spatial shift of damages, as in our case study (see Figure 4). Optimally, the selected measure(s) can shift the flood from an area with high vulnerability or high predicted damages towards an area with low vulnerability or low predicted damages without affecting any areas other than the designed retention areas. For the flood waves that the system was designed for, this often works very well (see for instance Table 5). At times, even carefully planned measures cannot avoid a certain amount of involuntary changes in the resulting inundation and areas previously not affected might be flooded. If the planned measures are effective, this involuntary increase in damages in a certain spatial location is more than compensated by the beneficial effects on the whole system (see for instance Table 5). However, even spatially limited deteriorations might be interesting to decision-makers and the summation of both beneficial and detrimental effects masks their existence. This effect is called spatial compensation.

If a flood management system's effectiveness is tested with flood waves for which the system was not specifically designed, more involuntary shifts in damage might occur (see the increased damages given in Table 6 and the dramatic increase in damage shown in Figure 4). This means that in safety-oriented flood retention, where measures were planned and tested based on a design flood wave, spatial compensation probably occurred less frequently and was thus less important. Risk-oriented flood retention entails taking into account all probable floods, which includes testing the flood retention system with flood water levels way beyond the design flood. Our results show that, especially when the flood retention system is overstressed, involuntary spatial shifts in damage can occur. Especially in these cases, spatial compensation achieved high levels (see

Table 6). Thus, especially in risk-oriented flood retention management, avoiding spatial compensation seems to gain importance.

In this paper, we have discussed spatial compensation during the summation of damage of individual floods. However, in risk-oriented flood retention, the integral of the total damage ex ante for all probable events has to be calculated. This means that, if spatial compensation is not eliminated for each individual return period, compensation across return periods might occur during the calculation of the integral. In other words, the detrimental effects that show in return period 1:x might be compensated by beneficial effects on floods with a return period 1:y. This sort of 'probabilistic compensation' can be avoided if amelioration and deterioration are aggregated separately. Again, this enhances the importance of avoiding spatial compensation.

Another aspect that warrants discussion is the weights that are attributed to the criteria in many MCDM algorithms. If the scientist aggregates a criterion's amelioration and deterioration, and thus allows spatial compensation, the amelioration and deterioration are inherently attributed equal weights. In other words, the improvement in one spatial location is valued equal to the degradation in another area. This valuation is not to be made by the scientist, but by the decision-maker(s); therefore, both data sets are to be communicated. If spatial compensation is avoided and improvement and degradation are treated separately, the decision-maker(s) can opt to value the avoidance of additional degradation over the increase in amelioration.

5 Conclusion

If an alternative's benefits in one spatial location outweigh or even veil the full extent of detriments that occur in another spatial location, spatial compensation occurs. In this work, we have demonstrated that by comparing summed up damages for different alternatives, spatial compensation can mask crucial information. Although comparing the sum of effects of different spatial extents is fairly common procedure, it is important to realize that if spatially dissimilar improvements and degradations are aggregated, commensurability is inherently – and often incorrectly – assumed.

It was demonstrated by analysing different spatial aggregation resolutions that spatial compensation was solely responsible for the errors in the final decision matrix. The MCDM application also showed that, based on a flawed decision matrix, the multi-criteria analysis is bound to prioritize a sub-optimal measure. This means that, valuable information may thus be distorted or withheld from stakeholders and decision-makers, which in turn may lead to flawed decision-making.

We have proven, based on both a fictional mathematical example and a case study, that the proposed aggregation techniques can very effectively avoid spatial aggregation, independent of different MCDM algorithms or spatial resolution levels.

Spatial equity, the relative spatial distribution of the summarized criteria, was also proven to be relevant in the decision-making process and can likewise be incorporated by the recommended aggregation techniques.

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