Existing levee system economic evaluation methodology

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Abstract. In France but also in other countries, levee system network are mostly composed of old levees, modified and reinforced during the past. In France, these systems, as road network, are considered as properties and financially as assets. Then the French Centre for Studies and Expertise on Risks, Environment, Mobility, and Urban and Country Planning (CEREMA) and Centre- Val de Loire Regional Direction of Environment Planning and Housing (DREAL) conducted a reflection to build a methodology for an economic evaluation of a levee system. This reflection is inspired by methodology based on asset replacement cost with a potentially depreciation reserve and methodology based on total economic value that takes into account benefits or provided services rendered by this asset. Therefore, the global economic value of a levee system is an average of structural cost balanced out with depreciation or bonus factors. The article details how structural cost is obtained with a levee system segmentation in homogeneous levee sections and unit prices and how depreciation or bonus are evaluated. Finally, this article discuss this methodology and its applicability on Loire levee systems with an example on Orléans levee system.

1 Introduction

In France, levee systems, just like road or other linear infrastructure networks, are considered as properties and financially as assets. To be taken into consideration in public accounts, the French Accounts Court (Cour des Comptes, 2016) demanded that an economic evaluation of such structures be performed (RNCE, 2016). Then the French Centre for Studies and Expertise on Risks, Environment, Mobility, and Urban and Country Planning (CEREMA) and Centre- Val de Loire Regional Direction of Environment Planning and Housing (DREAL) conducted an exploratory work on economic evaluation methodologies to lay the foundations for a reflection on methods for levee systems economic evaluation.

The purpose of this article is to review conditions of levee economic evaluation, to propose a calculation methodology and then to discuss its applicability on the River Loire's levee system.

2 Levee economic evaluation conditions

2.1 Economic evaluation methodologies of tangible real estate assets

Economic evaluation methodologies of tangible real estate assets are based on two value types : on the one hand, “exchange value” or “market value” with a price that

can be obtained on a marketplace or determined by costs calculation and on the other hand “use value” corresponding to profits or future economic advantages rendered by asset usage [6].

Then, we can distinguished two types of evaluation methodologies: those based on asset replacement cost, eventually depreciated and those based on expected advantages or rendered services evaluation. For that, the Total Economic Value (TEV) of the asset has to be determined (Pearce et al., 2006).

2.2 Levees economic evaluation particularities

For levee systems and big linear infrastructures, venal value (market value) and use value are clearly distinct and their evaluations are complex. As levees are not classic goods, their venal value cannot be evaluated by simple prices analysis. This value has to be calculated with costs. Then, methodology based on depreciated replacement costs seems to be the only practical methodology. By the way, in France this methodology is recommended for roads, highways and dams (DEF, 2016).

Practical application of this methodology requires deep knowledge of levee structural components, of their conditions and maintenance or reparation costs to determine global cost of a levee system and then evaluate its replacement cost. Bonus and drop in value can be applied on the entire levee system regarding its use value

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or partially on certain components regarding local levee sections performance or regarding their historical patrimonial value. It becomes then essential and a prerequisite to have a fine assessment of levee system in term of main structures, components, functions and performance.

Use value of a levee system is first of all linked to its flood protection function. Therefore, this value is directly linked to the global value of protected goods or properties for a maximal expected level of performance of the levee system. However, levees could have secondary functions which values can also be important and complex to appreciate (roads in levee crest, agricultural, recreational, environmental ...functions). Levee systems could also have a high patrimonial value in historical sites and be classified as UNESCO World Heritage like Loire Valley. The Figure 1 illustrates the different components of total economic value (TEV) applied to levee cases.

The combination of all these use values make difficult the evaluation of levee systems economic value. Nevertheless, this evaluation can take advantage of damages costs analysis in protected areas often realized for financing demands in national action programs (French Big Rivers programs, PAPI...).

Figure 1. Total Economic Value for a Loire Levee system (Cerema after [7])

Regarding above elements, the methodology proposed for levee system economic evaluation is based on the combination of (i) replacement cost of asset, eventually globally or partially depreciated, (ii) evaluation of some assessable rendered services or expected advantages that could be part of total economic value (TEV) of this asset.

3 Levee system economic evaluation methodology

In France, there are more than 9000 km of flood protection levees in fluvial, torrential or coastal environments. State levees represent about 10% of this length but often protect main issues. These state levees are very old earthen levees (sometimes Middle Ages levees), heterogeneous because they were often made wider, increased, repaired, reinforced since they were built. That is typically the case for Loire levee systems with a total length of 700 km managed by local Territories Departmental Directions with the concourse of DREAL Centre Val de Loire. We built and illustrate the following methodology on these levees, very well documented.

3.1 Typology of state levees

Forms of existing old levees and their heterogeneous structures result in successive rebuilding and raisings following each historical flood events. Historical levees are mainly alluvial (sand, silt and clay) earthen embankments protected or reinforced with masonry components (stone made revetments, quays, walls, low walls...), containing overflow design structures like spillways and specific civil works structures to manage water flows (culverts, sluice gates...).

Thus, a levee system can be considered as a succession of “homogenous” segments, more or less long, interrupted by singular civil works or culverts. Each segment contains an historical embankment earthen core reinforced or not with different components or simply widened or increased with another embankment material. Therefore, a structural and functional study of the levee system can easily give the system separation in “homogenous” segments and specific works (Figure 2).

Figure 2. Description of the levee system separation in representative levee segments and profiles (Durand E., 2016)

We describe each levee segment with a representative topographic profile (Figure 3) composed by a core, structural (wall, spillways...) or functional components (drainage system, roads...) or reinforcement ones (thickening fill, riprap, cutoff wall...). The knowledge of unit prices (linear, surface or volumetric) of these components enables to evaluate economic value of the profile then segment and finally the entire levee system value.

Figure 3. Levee segment separation in unit structural, functional or reinforcement components (Cerema)

3.2 Calculation methodology description

Calculation methodology is based on hypothesis that levee system global economic value is obtained by weighting “structural value” with depreciative coefficients related to functional levee state or with bonus coefficients related to patrimonial or use value (or rendered services). Then, the methodology consists in multiplying average

levee system structural cost (including its current components), C_s , by weighting coefficients K_i . The following Equation (1) gives the weighted global economic value C :

$$C = C_s \cdot K1 \cdot K2 \cdot K3 \cdot \dots \cdot Kn \quad (1)$$

With:

C_s : average structural cost of the levee system, $K1$: coefficient related to actual levee performance, $K2$: coefficient of provided service related to prevented damages, $K3$: coefficient related to patrimonial value of levee system, Kn : others coefficient that could be added.

Levee system economic structural evaluation C_s based on levee segments separation in unit structural, functional and reinforcement's components (see figures 2 and 3) can be obtained with following formula:

$$C_s = C[\text{noyau}] \times \sum_{i=1}^n [L(P_i) \times S_{P_i}] + \sum_{x=1}^m [C[\text{renf}_x] \times L[\text{renf}_x]] + \sum_{y=1}^p C[\text{Ouv}_y] \quad (2)$$

With:

$C[\text{noyau}]$ the average volumetric cost of levee embankment; P_i the profile number representative of a levee length L ; n the total number of profiles on the levee system; S_{P_i} the trapezium surface of levee core P_i profile; x the reinforcement type with a unit linear cost $C[\text{renf}_x]$ and present on $L[\text{renf}_x]$ length; $C[\text{Ouv}_y]$ the cost of a specific works (sluice gate, spillway...); m the number of reinforcement and p the number of specific works existing on the levee system.

3.3 Average volumetric cost of levee core

Average volumetric cost calculation of levee core $C[\text{noyau}]$ is function of its geometry and well knowledge of levelling works unit costs. If exact core geometry is unknown, unit trapezium surface V_u can be approximated easily with charts regarding levee height, crest widths and banks slopes (Figure 4).

Figure 4. Trapezium built by embankment or levee core.

The unit volume V_u is given by :

$$V_u = [(B + l) \cdot h] / 2 \quad (3)$$

Several studies conducted from 2012 to 2014 indicate that average levelling works unit cost P_u is 13 € to 22 € [13] for 1 cubic meter of material extracted, brought on site and put in place. This cost is very dependent on material availability next to the working site. Then, to evaluate levee core building cost $C[\text{noyau}]$ you just have to multiply unit volumes V_u by unit costs P_u as follow:

$$C[\text{noyau}] = P_u \cdot V_u \quad (4)$$

Charts or tables, function of levee height, bank slopes and crest width can rapidly be obtained to get unit cost of trapezoidal levee core section construction. Table 1 is an example for a unit price of levelling work of 20 €/m³. Same principle is applied to get unit volumes and costs of widening reinforcements if such reinforcement exist on levee system (see Figure 3).

		Unit costs C[noyau] (€/m) for a trapezoidal levee core and for levelling unit cost of 20 €/m³											
Levee crest width (m)		2				3				4			
Bank slope (V/H)		1/1	1/2	1/2,5	1/3	1/1	1/2	1/2,5	1/3	1/1	1/2	1/2,5	1/3
Levee height (m)													
1		60	80	90	100	80	100	110	120	100	120	130	140
2		160	240	280	320	200	280	320	360	240	240	360	400
3		300	480	570	660	360	540	630	720	420	420	690	780
4		480	800	960	1120	560	880	1040	1200	640	640	1120	1280
5		700	1200	1450	1700	800	1300	1550	1800	900	900	1650	1900
6		960	1680	2040	2400	1080	1800	2160	2520	1200	1200	2280	2640
7		1260	2240	2730	3220	1400	2380	2870	3360	1540	1540	3010	3500
8		1600	2880	3520	4160	1760	3040	3680	4320	1920	1920	3840	4480

Table 1. Unit cost evaluation $C[\text{core}]$ (€/m) for a trapezoidal levee function of its height, bank slopes and crest width.

3.4 Costs of surface levee protective coatings

Generally, fluvial or coastal flood protection levees own protective coating that is grass cover as a minimum. We find in literature an average unit price of 1 €/m² for a simple grass cover. For a masonry protective coating, unit prices are very dependent with quarry proximity and local labor cost. As a first approach we choose a unit price of 100 €/m² for masonry coatings construction. Unit surfaces of trapezoidal levee are given in Table 2 for different heights and slopes.

Unit Surfaces S_i (m ² /m) of trapezoidal levee bank				
Bank slope (V/H)	1/1	1/2	1/2,5	1/3
Levee height (m)				
1	1,4	2,2	2,8	3,2
2	2,8	4,5	5,5	6,3
3	4,2	6,7	8,3	9,5
4	5,7	8,9	11,1	12,6
5	7,1	11,2	13,8	15,8
6	8,5	13,4	16,6	19,0
7	9,9	15,7	19,4	22,1
8	11,3	17,9	22,1	25,3

Table 2. Levee bank unit surfaces S_i (m²/m) function of its height and bank slopes.

3.5 Levee reinforcements costs

There are several types of levee reinforcements. For historical levees such as Loire levees, it is impossible to know precisely, all kind of reinforcement put in place during centuries. Nonetheless, in this study we try to list main reinforcement types, which are: riverside levee widening, protected side widening with drainage system at the toe, sheet piling or soil-mixing cut-off wall, riverside ripraps. This non-exhaustive list can be completed to refine levee economic evaluation. Based on DREAL Centre Val de Loire 2010 to 2016 operational works, unit reinforcements prices $C[\text{renf}_x]$ were obtained and are set in Table 3.

Type of works		Ratio (€ TTC/ml) 2016 value
Quay wall Reinforcement ¹		26,000
Reinforcement de pied de levee ¹		865
Levee core reinforcement ¹	Sheet piles cut-off wall	2,600
	Soil mixing cut-off wall	980
Widening reinforcement ²	Levelling with toe drainage system on protected side and with impermeable soils on riverside	570
	with house purchasing	3,850
Embedded houses traitment ³	without house purchasing	1,550
	Slope 2/1	810
Masonry protective coating repairs ³	Slope 3/2	650
	Slope 3/1	1150

¹ Evaluation based on 2010 to 2016 state levees reinforcement works
² Evaluation based on 1970 Levees reinforcement program on Loire-et-Cher Department (45km of levees)
³ Evaluation based on DDT45 maintenance contract for a 5 meters high levee

Table 3. Unit cost (€ TTC/ml) of principal reinforcements of Loire levees (DREAL Centre Val de Loire, 2016).

To get global reinforcement cost of a levee system, you just have to precise what reinforcement is present on which segments and on which length $L[\text{renf}_x]$.

3.6 Costs of specific civil engineering works

Civil works components on levee systems generally enable flows management through levees. For example we can find sluice gates, see gates (Figure 5) or drying culverts installed in lowest topographic points of protected areas, naturel or artificial drainage channels.

Figure 5. Seagate present on Chalonnes-sur-Loire levee system (©Cerema)

More important structures like spillways or quays are also present on levees (Figure 6). Their costs, $C[\text{Ouv}_y]$ in formula (2) must be case-by-case appreciated and no linear unit price can easily be determined.

Figure 6. View of masonry downstream slope of spillway, near Blois, France (©E Durand).

3.7 Costs of land property and supported structures

In economic evaluation, land property that supports levee system is also taken into account with an average unit price 1 €/m². Levee width (see Figure 4) and if necessary constraints surfaces on both sides of levees enables to evaluate right of way surface. Furthermore, levees often support roads or other infrastructures on their crests [11] which represents an additional specific cost of economic levee evaluation.

3.8 Evaluation tool to evaluate structural levee cost

In order to facilitate economic structural cost evaluation of linear structures as levee systems, reinforced or not, with or without protective coatings, supporting roads or not, a spreadsheet can helpfully be used. With geometry data, even simplified ones, elementary surfaces, volumes and lengths can easily and automatically be calculated.

For central Loire levee systems, we naturally reused CARDigues tool [15] and adapted it to above presented methodology.

Figure 7. Characteristics of a typical profile used in CARDigues methodology [15]

Indeed, CARDigues tool was used on 46 Loire levees hazards studies and geometry data (shown on Figure 7) are already input for each representative profile of levee segment, every 50 ml length (generally). Presence and nature of reinforcements are also available data. We just added missing surface and volumetric calculations, and unit costs calculation defined above, based on unit prices fixed by user. Figure 12 is an extract of calculation tool filled with Orléans levee system data.

To this construction structural cost of levee and its reinforcements, we must add levee system specific components costs.

3.9 Coastal levee's particularities

For costal levee systems we can considered that it is composed with following elements: (i) earthen levees; (ii) natural works like dunes, beaches; (iii) civil-work structures (see wall, groynes etc.); (iv) hydraulic structures (culvert, see gates, sluice gates etc.). Differences with fluvial levee systems can be identified such nature or design of protective coating or reinforcements (rip rap, tetrapod...) but part of coastal levees segments are just sandy core levees with a grass coating (see Figure 8).

Figure 8. Typical profile of a coastal earthen levee of Somme's Bay, north of France [12]

Therefore, we have proposed to use the same methodology for coastal levee economic evaluation. For these systems, financial weight of specific civil-works will represent a most important part of total evaluation than fluvial levees.

3.10 Weighting coefficients calculation

In this methodology, we have suggested in formula (1) to introduce weighting coefficients for levee system global economic value.

The K1 coefficient is function of actual levee performance in comparison to expected performance. K1 expresses the difference between expected (or chosen) protection level, N_{obj} , and the actual security level of the levee system, N_s . Both levels are defined in levee system hazards studies, required in French levee system regulations. We have proposed for K1 the following formula:

$$K1 = 1 - (N_{obj} - N_s) / (N_{obj} - N_{réf}) \quad (5)$$

with $N_{réf}$ the riverside levee toe level i.e. level of first hydraulic charge on levee.

K2 coefficient represents rendered services regarding prevented damages during flood events. Economic analysis of infrastructures such as levee system in flooding areas are generally based on costs-benefits analysis [8,14]. In such studies the average annual damages (DMA), with or without levee system, is defined to evaluate average annual prevented damages (DEMA) due to levee system. We then have proposed for “use value” or rendered services value coefficient the following K2 definition:

$$K2 = 1 + \frac{(DEMA)}{(DMA \text{ without levee system})} \quad (6)$$

With:

$DEMA = (DMA \text{ without levee system} - DMA \text{ with levee system})$.

We have also add a K3 coefficient in methodology. It represents patrimonial value of levee system. Several levees are very old ones and own a specific value because systems interact on landscape morphology. It is the case for levees in Loire Valley classified as Unesco World heritage. Unfortunately, we have not find yet an easy way to define K3.

Other coefficients could be added later in methodology as knowledge on levee systems costs will increased.

4 Loire levees: practical application

The Middle Loire levee system is composed by 50 levees that protect 300 000 inhabitants in potentially flooded areas. Between XVIth and XXth centuries, 3 or 4 big flood events occurred during each century and caused lot of breaches and damages. The last one was the 1907 flood event and the absence of any major flood event for more than 100 years is considered as a singularity and not as a decrease of hazard level. A huge flood event like in XIXth century would cause huge damages evaluated to 8 billion Euros on river Loire basin.

Figure 9. Maps of Orléans levee system on river Loire, France (Cerema -Source:Scan100® – IGN©)

Between 2012 and 2017, managers conducted 46 hazards studies on state levee Loire systems and safety levels N_s were then defined. Maintenance and reinforcement recommendations were proposed to upgrade N_s . The 3 main levee systems on river Loire are Orléans (65 000 inhabitants and 44 km long), Tours (135 000 inhabitants and 56 km long) and Authion (62 000 inhabitants and 80 km long). Orléans hazards study [10] was the first study on Loire levees and enables the development of methodology and CARDigues Tool used on other levee systems.

PROFILE IDENTIFICATION (From CARDigues)				Topographic data (From CARDigues)													

Figure 10. Extract of CARDigues Tool [15] – Profile geometry data.

Orléans levee system is 43,55 km long (see Figure 9). CARDigues's model of this system contains 872 profiles characterized by 7 specific points with (X, Y and Z) coordinates for each of them (cf. figures 7 and 10). Informations such civil-work structures, masonry wall, spillway and reinforcements are also data available in CARDigues (see Figure 11). Economic evaluation tool take this information and calculates, for each profile and for the entire system : levee embankment and core volumes, reinforcements volumes, bank slopes surfaces, right of way surface...

PROFILE IDENTIFICATION (From CARDigues)				STRUCTURAL DATA AND EXISTING ANOMALIES (From CARDigues)														BET To Levee 2016									
Profile	Levee Type	Height	Location	Line and Name of Levee	Segment	Concrete Structure Type	Substrate Type	Reinforced Concrete Structure	Existing Structure	Protected Side Structure	Side Structure Type	Side Structure Height	Side Structure Width	Side Structure Length	Side Structure Area	Side Structure Volume	Side Structure Weight	Side Structure Cost	Side Structure Cost	Side Structure Cost	Side Structure Cost	Side Structure Cost	Side Structure Cost	Side Structure Cost	Side Structure Cost	Side Structure Cost	Side Structure Cost
101	101	101	101	101	101	101	101	101	101	101	101	101	101	101	101	101	101	101	101	101	101	101	101	101	101	101	101

Figure 11. Extract of CARDigues Tool [15] – Profile structural and reinforcement data.

Then, for Orléans levee system we have following results: the volume of embankment is 4.1 Mm³ (Millions of cubic meters) including 3.6 Mm³ for core and 0,44 Mm³ for protected side widening reinforcements and 0.06 Mm³ for riverside ones. It contains 550 ml of sheet piles cut-off wall and 7.45 km of soil-mixing cut-off wall. Total surface of riverside masonry protective coating is 490 000 m².

Based on unit prices shown in Figure 12, the structural value of Orléans levee system, without property value and without specific civil-work structures values (walls, spillways, roads...) is in first approach evaluated to 172 M€ (in 2016 Euro economic value). We then proposed to keep in mind a total structural value Cs of 200 M€ that is to say a structural value of 4 600 €/ml of levee.

Riverside reinforcement unit cost (Euros 2016/ml)	Protected side reinforcement unit cost (Euros 2016/ml)	Ripraps unit cost (Euros 2016/ml)	Soil mixing cut-off wall unit cost (Euros 2016/ml)	Sheet piling cut-off wall unit cost (Euros 2016/ml)	Masonry protective coating unit cost (Euros 2016/m ²)	Core levelling unit cost (Euros 2016/m ³)	
570,00	570,00	865,00	980,00	2600,00	100,00	2063,00	
Riverside reinforcement cost (€)	Protected side reinforcement cost (€)	Ripraps cost (€)	Soil mixing cut-off wall cost (€)	Sheet piling cut-off wall cost (€)	Masonry protective coating cost (€)	Levee core cost (€)	TOTAL levee system Cost (€) without property and civil-work components costs
3 733 500 €	16 159 500 €	3 287 000 €	7 301 000 €	1 430 000 €	49 017 037 €	90 772 000 €	171 700 037 €
2%	9%	2%	4%	1%	29%	53%	100%

Figure 12. Extract of structural levee system cost calculation tool adapted from CARDigues tool and applied on Orléans system [15]

On this levee system, safety level Ns was defined as the level of the flood of 70 years return period i.e. 4.67 m (95.15 m NGF) at Orléans hydraulic gauging station [10]. Reference level N_{réf} is defined at 3.75 m (94.22 m NGF) and corresponds to a 20 years' return period flood. The expected protection level N_{obj} corresponds to a 200 years return period flood i.e. 5.77 m (96.25 m NGF).

With these elements and according to formula (5), K1 coefficient for Orléans levee system is equal to 0.455 regarding its actual performance. It represents a depreciative coefficient of 45,5% of its actual structural value. We can noticed that future operational works planned on this system will increased safety level Ns to 5.34 m (100 years return period flood event) and then K1 will be equal to 0.578.

For Orléans valley the DMA without levee system was established to 6.6 M€. With actual levee system (Ns based on 70 years return period), the DMA is equal to 6.25 M€. Then, average annual prevent damages DEMA is the equal to 0.35 M€.

K2 coefficient, according to formula (6) is equal to 1.053 for Orléans levee system. It represents a 5.3 % bonus of levee system according to our methodology. With future operations, DEMA will be 0.60 M€ i.e. K2 equal to 1.09.

Then, for Orléans levee system, the global economic evaluation Corléans, according to formula (1) is equal to Corléans = 200 x 0,455 x 1,053 = 96 M€. With future operational works, this value will be 115 M€.

We just like to remind to readers that this is an estimation of levee economic evaluation based on a new methodology that needs to be refined and more largely tested on other levee systems to be approved.

5 Conclusions

A new methodology for levee systems economic evaluation was developed by Cerema and DREAL Centre-Val de Loire and presented in this article. This methodology consists in a levee global evaluation using average structural costs of levee construction, weighted with different bonus or depreciative coefficients.

Average structural cost is obtained using unit costs, levee geometry and reinforcements components. Firstly applied on Orléans levee system, along river Loire in France, this methodology gives first results for levee economic evaluation. It will be tested on 46 others river Loire levee systems to make this methodology and weighting coefficients more accurate.

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