DRAFT REPORT

Evaluation of PAGDP plans in Madagascar with the LANDSIM-R prototype

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Summary

This report presents the methodology and results regarding the application of the LANDSIM-R toolbox for simulation of the Sustainable Land Management (SLM) interventions foreseen in the PAGDP planning process. For each of the five landscapes Marovoay, Bealanana, Andapa, Soanierana Ivongo, and Iazafo, maps of current erosion hotspots are presented along with the potential impact of different SLM interventions. For Marovoay and Bealanana, specific investment portfolios based on these results and the PAGDP plans are proposed and simulated, and evaluated in terms of their impact on soil erosion, downstream sediment yield, and hydrological dynamics.

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1 Introduction

1.1 Background

Within the Land Use Planning for Enhanced Resilience of Landscapes (LAUREL) project, a Land Use Change Simulation Platform (LANDSIM-P) has been developed with the objective to support policy makers by providing an integrated assessment of the impact of current and future land use and land management on the status and risk of land degradation and land-based ecosystem services. Part of the LANDSIM-P instrument is a decision support tool at the regional level, which is used to simulate water availability and erosion under different scenarios related to sustainable land management (SLM) activities and land use change. This regional-scale toolbox (LANDSIM-Regional, or LANDSIM-R) should support planning processes within the Sustainable Landscape Management Project (PADAP). As part of the LAUREL project, FutureWater has configured five catchment models with LANDSIM-R and provided capacity building to PADAP staff in using LANDSIM-R, evaluating its results in a SLM planning context, and updating and improving the toolbox with additional data.

As an additional activity within LAUREL, FutureWater was requested to perform a set of LANDSIM-R simulations based on the SLM plans (PAGDP) created under the PADAP program, for each of the five pilot catchments. This report describes the approach and results of this activity and provides a brief outlook toward future LANDSIM-R application and capacity building.

1.2 Objective and scope

The current activity under the LAUREL project involves the application of the LANDSIM-R prototype to the interventions proposed in the PAGDP plans. The main objective of this activity is to identify spatially explicit locations where these interventions, as proposed in the PAGDP plans, would be the most effective in terms of reducing erosion in the five pilot landscapes. In addition, given the special interest of the PADAP program in the Marovoay and Bealanana regions, the analysis for these two goes one step further by evaluating the impact of a concrete package of interventions on downstream sediment yield and water availability.

2 Methodology

2.1 Using LANDSIM-R to simulate impact of SLM interventions

In general, a typical application of LANDSIM-R involves the extraction of catchment-specific data using its pre-processing interface in QGIS. The model configuration file that is created by the QGIS plugin is then used to run the SPHY[1] model tailored to Madagascar conditions. The main results of LANDSIM-R are spatial and temporal outputs (maps and graphs) of three key strategic variables identified in the LAUREL project: soil erosion, river discharge, and sediment yield. In the LAUREL project, separate models were created in this manner for the five PADAP pilot catchments of Marovoay, Bealanana, Andapa, Iazafo, and Soanierana Ivongo. To the extent possible, calibration and quality control procedures were implemented for these pilot models.

Figure 1. Main components of the LANDSIM-R toolbox.

The initial LANDSIM-R results produced in this way represent the "baseline" situation, i.e. the 2005 – 2015 conditions based on the climatology, land use, vegetation cover dynamics, and other model inputs included in the national database. To support SLM decision making, these baseline results should be compared with simulation results of interventions implemented in the catchment. To this end, the LANDSIM-R user can configure a spatial map of interventions, which indicates the locations and type of interventions introduced in the model. The following SLM interventions can be simulated with the LANDSIM-R prototype:

- Terracing
- Reforestation
- Forest restoration
- Agroforestry
- Reduced tillage

The LANDSIM-R prototype was developed with the following applications in mind:

1. Identification of erosion hotspots in a catchment
2. Exploring impact of a land management (SLM) measure across a catchment, to identify suitable areas for implementation
3. Assessing impact of upstream SLM measures on downstream sediment yield
4. Assessing impact of upstream SLM measures on downstream water availability
5. Other scenario runs, such as climate change impacts

Application 1 involves only the assessment of baseline conditions, to identify problematic areas that should be targeted with SLM interventions. Applications 2 – 4 require baseline simulations as well as SLM scenarios, and the evaluation of differences between the results of the different model runs.

[1] *www.sphy.org*

This report describes two activities: (i) the implementation of Application 1 and 2 for all five PADAP catchments, and (ii) the implementation of Applications 3 and 4 for the Marovoay and Bealanana catchments. The approach to these two activities is further elaborated in Sections 2.2 and 2.3 respectively.

2.2 Supporting spatial planning of PAGDP interventions

2.2.1 Approach

The purpose of this activity is to produce maps of soil erosion reduction that can be achieved by implementation of SLM interventions across the five catchments. The spatial distribution of these interventions was decided based on criteria related to land use, terrain slope, historical deforestation, and geographical restrictions prescribed by the PAGDP plans (see Paragraph 2.2.3 for further details). The scenarios constructed in this way are referred to below as "full interventions", i.e. they are assumed to cover all potential sites where these interventions can be realized. For each catchment, only the interventions are included which are mentioned in the corresponding PAGDP plan.

The following steps were taken:

- Performing baseline runs (2005 – 2015) for all 5 PADAP catchments to produce maps of erosion rate across the catchments;
- Development of scenarios of "full interventions", i.e. hypothetical implementation of the interventions for all locations meeting certain criteria. In cases where communes and/or sous-paysages are specified in the PAGDP plans, the corresponding interventions were only included in the model for these areas (see Paragraph 2.2.3);
- Analysis of the erosion rate reduction achieved by the implementation of these interventions across the 5 catchments, to identify sites where the interventions are expected to be the most effective. This is key information to support spatialization of the interventions proposed in the PAGDP plans.

2.2.2 Interventions identified per landscape

The table in this section lists for each catchment the interventions included in the PAGDP plans which can be simulated by LANDSIM-R, as well as their specific characteristics.

Table 1. Relevant SLM interventions considered for Marovoay.

Description	Surface area (ha)	Location	Budget ($)	
			2020-2021	*2020-2022*
Travaux de reboisement par des espèces autochtones	1600	à l'intérieur et aux alentours directs du Parc National d'Ankarafantsika	412,300	930,000
Travaux de reboisement à vocation énergétique et bois d'œuvre	800	CR de Marosakoa, Ambolomoty, Tsararano et Anosinalainolona	275,000	320,000
Développement d'activités économiques et agricoles de conservation durable pour les Exploitants des zones périphériques d'Ankarafantsika	150	Anosinalainolona, Tsararano, Marosakoa		

Table 2. Relevant SLM interventions considered for Bealanana.

Description	Surface area (ha)	Location	Budget ($)	
			2021	2022
Appui aux activités de reboisement sur les versants dégradés et/ou menacés par les phénomènes d'érosion dans le sous-paysage de Bealanana	150	SP Bealanana	55,250	32,250
Appui aux activités de reboisement sur les versants dégradés et/ou menacés par les phénomènes d'érosion dans le sous-paysage d'Ambatosia	150	SP Ambatosia	55,250	32,250
Appui aux activités de reboisement sur les versants dégradés et/ou menacés par les phénomènes d'érosion dans le sous-paysage d'Ambatoriha	190	SP Ambatoria	110,500	64,500
Développement de l'agro-écologie et de l'agroforesterie visant à limiter l'érosion et restructurer le sol dans le sous-paysage d'Ambatosia	10	SP Ambatosia	80,100	23,900
Développement de l'agro-écologie et de l'agroforesterie visant à limiter l'érosion et restructurer le sol dans le sous-paysage de Bealanana	10	SP Bealanana	65,000	18,300
Développement de l'agro-écologie et de l'agroforesterie visant à limiter l'érosion et restructurer le sol dans le sous-paysage d'Ambatoriha Est	10	SP Ambatoria	47,100	25,800

Table 3. Relevant SLM interventions considered for Andapa.

Description	Surface area (ha)	Location	Budget ($)	
			2020	2021-2022
Aménagement de terrasses sur des versants abrupts (Terracing)	20	Antsahameloka, Andasibe Kobahina	-	43,000
Promotion et développement de l'Agroforesterie (aménagement, extension, densification, enrichissement), …)	142	Ankiakabe Nord, Andasibe Kobahina, Ambodidivaina, Bealampona, Ambodimanga I, Matsohely, Andranomena, Andranotsara, Belaoko Marovato, Marovato	54,000	436,000
Reboisements individuels et communautaires sur les versants dégradés	2568	Marovato, Andasibe Kobahina, Belaoko Marovato, Betsakotsako, Andranotsara, Matsohely, Andranomena, Ambodidivaina, Ambodiangezoka, Andapa	-	105,000
Restauration forestière	150	AP COMATSA	20,000	60,000

Table 4. Relevant SLM interventions considered for Soanierana Ivongo.

Description	Surface area (ha)	Location	Budget ($)	
Stabilisation des flancs de collines/prévention contre la dégradation et l'érosion du sol (reboisement)	150	Ambahoabe, Andapafito, Antenina, Ambinanisakana, Antanifotsy, Fotsialanana, Manompana, Ambodiampana, Soanierana Ivongo	33,400	349,000
Restauration des paysages forestiers	750	Ambahoabe, Andapafito, Antenina, Ambinanisakana, Antanifotsy, Fotsialanana, Manompana, Ambodiampana, Soanierana Ivongo	1167000	1745000

Table 5. Relevant SLM interventions considered for Iazafo.

Description	Surface area (ha)	Location	Budget ($)	
Gestion des ressources naturelles (02 TGRN -stabilisation des flancs de collines/prévention contre la dégradation et l'érosion du sol	150 ha de reboisem ent annuel	Maromitety (Analabe)	88,000	154,000

2.2.3 Full intervention scenario definition

Full intervention scenarios were developed for each catchment according to the SLM types and administrative boundaries, subcatchment delineation and other geographical locations as indicated in Tables 1 - 5. In addition, various environmental variables were used to set criteria for implementation of the interventions. For example, a minimum terrain slope was assumed as a threshold for several SLM activities. Terracing is by definition applied to sloping terrain, and reforestation in Madagascar is typically implemented to stabilize hillslopes. This slope threshold differs per model, due to e.g. differing cell sizes. Land use type was taken as another decisive factor, with e.g. terracing and agroforestry only relevant for agricultural land use classes. To identify areas suitable for reforestation, use was made of forest loss over the 2001-2016 period according to the Global Forest Change dataset of University of Maryland.

Table 6 provides an overview of all intervention types simulated for the five catchments and assumptions made in developing the scenarios. Total surface area reported in the table corresponds with the area indicated in the intervention maps (Figures 2 – 7), and represents the potential area where these interventions could be applied according to the criteria used in this analysis. Areas of reforestation and forest conservation are summed in the tables, as these represent the same land use transition in the model (conversion to closed forest). For Andapa, both terracing and agroforestry are considered in the PAGDP plans. Since these interventions overlap in terms of suitable area (agricultural land with a certain slope), two separate intervention maps were created for Andapa. Furthermore, it should be noted that the reduced tillage intervention was simulated for Marovoay to represent the conservation agriculture practices considered for that region. In reality, this will likely encompass a package of different practices, including reduced tillage.

Table 6. Overview of all "full intervention" scenarios

Catchment	Intervention	Slope threshold	Surface area (ha)	Criteria
Marovoay	Reforestation (within and adjacent to National Park)	>3%	2710	All area that is not closed forest and has experienced forest loss in 2000-2016
	Reforestation for fuel and construction purposes	>3%		Area not within or adjacent to NP, with "herbaceous" land cover class (on hillslopes) or forest loss in 2000-2016
	Reduced tillage (conservation agriculture)	>3%	827	All agriculture within and adjacent to NP
Bealanana	Reforestation	>5%	2223	All area that is not closed forest and has experienced forest loss in 2000-2016
	Agroforestry	>10%	1606	All hillslope upland rice, cassava, maize
Andapa	Terracing	>10%	145	All hillslope upland rice, cassava, maize
	Agroforestry	>10%	428	All hillslope upland rice, cassava, maize
	Reforestation	>3%	3266	All area that is not closed forest and has experienced forest loss in 2000-2016
	Forest restoration	-		All open (degraded) forest in AP COMATSA
Soanierana Ivongo	Reforestation	>5%	57552	All area that is not closed forest and has experienced forest loss in 2000-2016
	Forest restoration	-		All open (degraded) forest
Iazafo	Reforestation	>10%	435	All area that is not closed forest and has experienced forest loss in 2000-2016

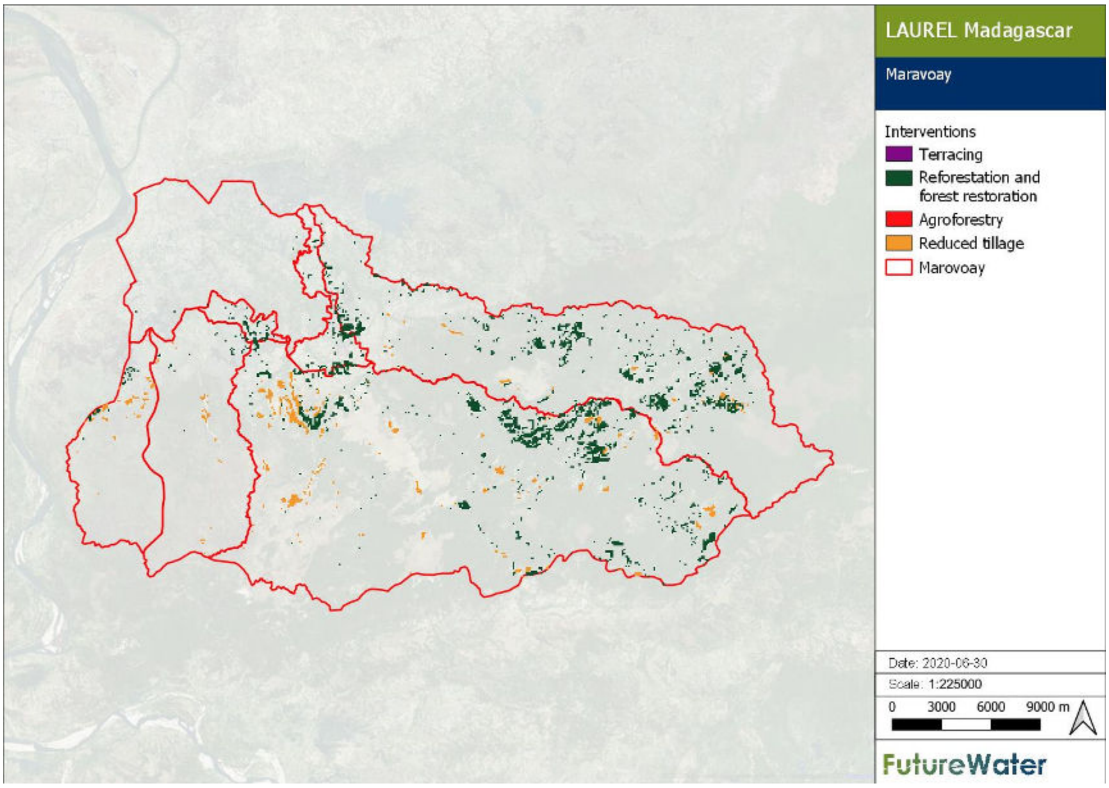


Figure 2. Interventions simulated for Marovoay.

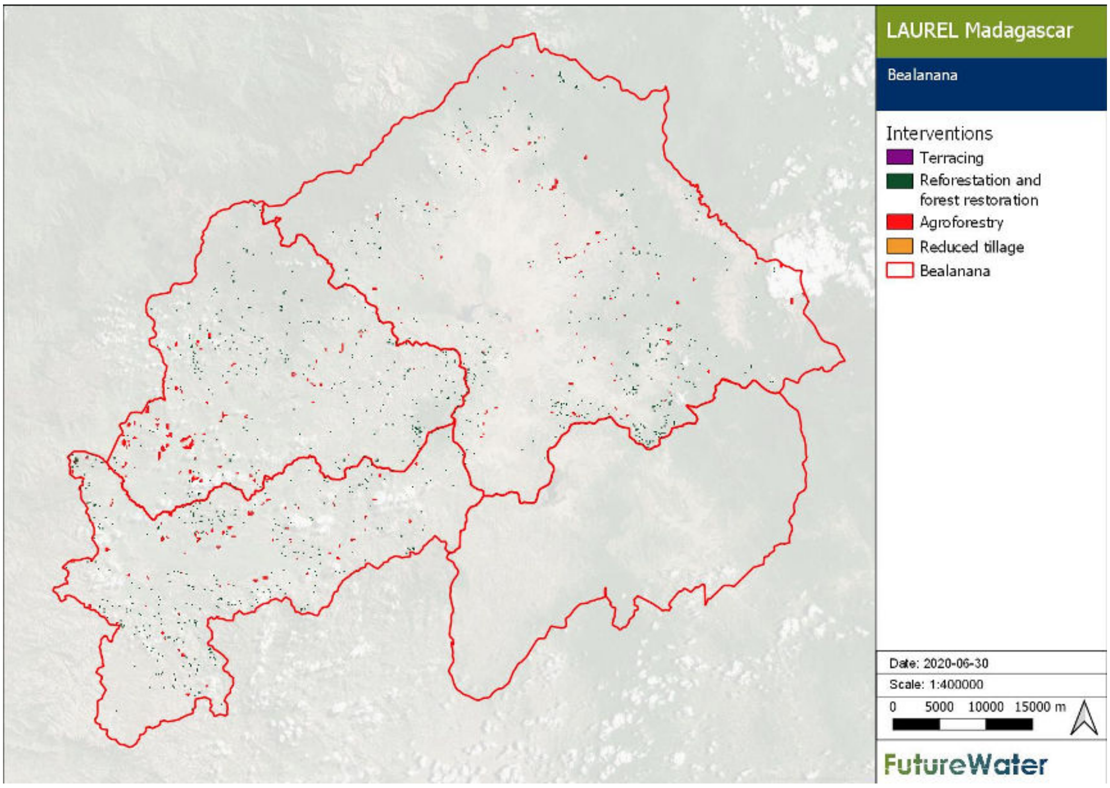


Figure 3. Interventions simulated for Bealanana.

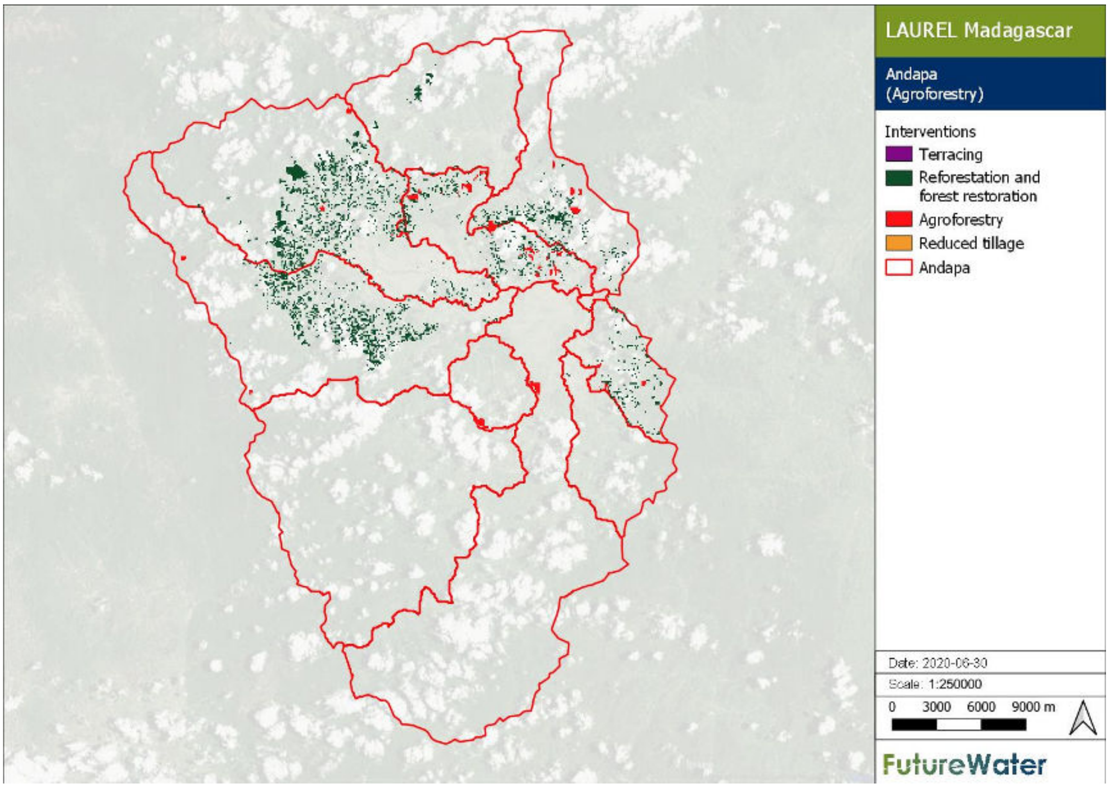


Figure 4. Interventions simulated for Andapa (Agroforestry scenario).

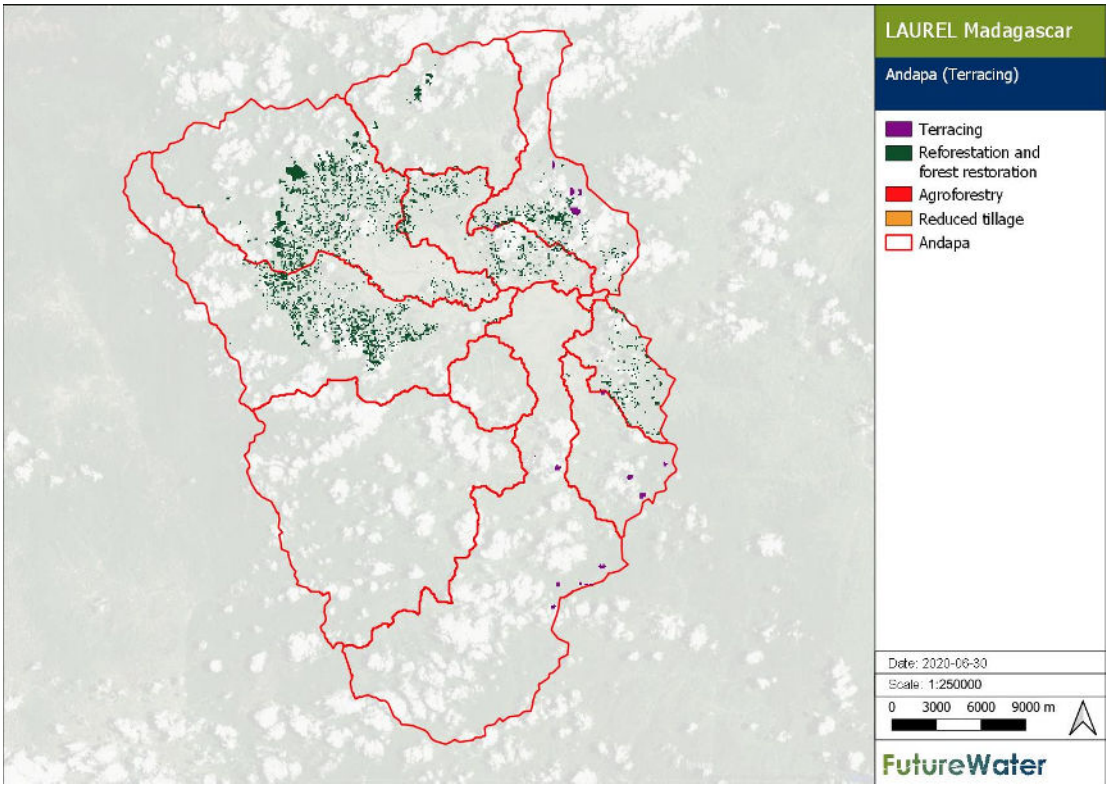


Figure 5. Interventions simulated for Andapa (Terracing scenario).

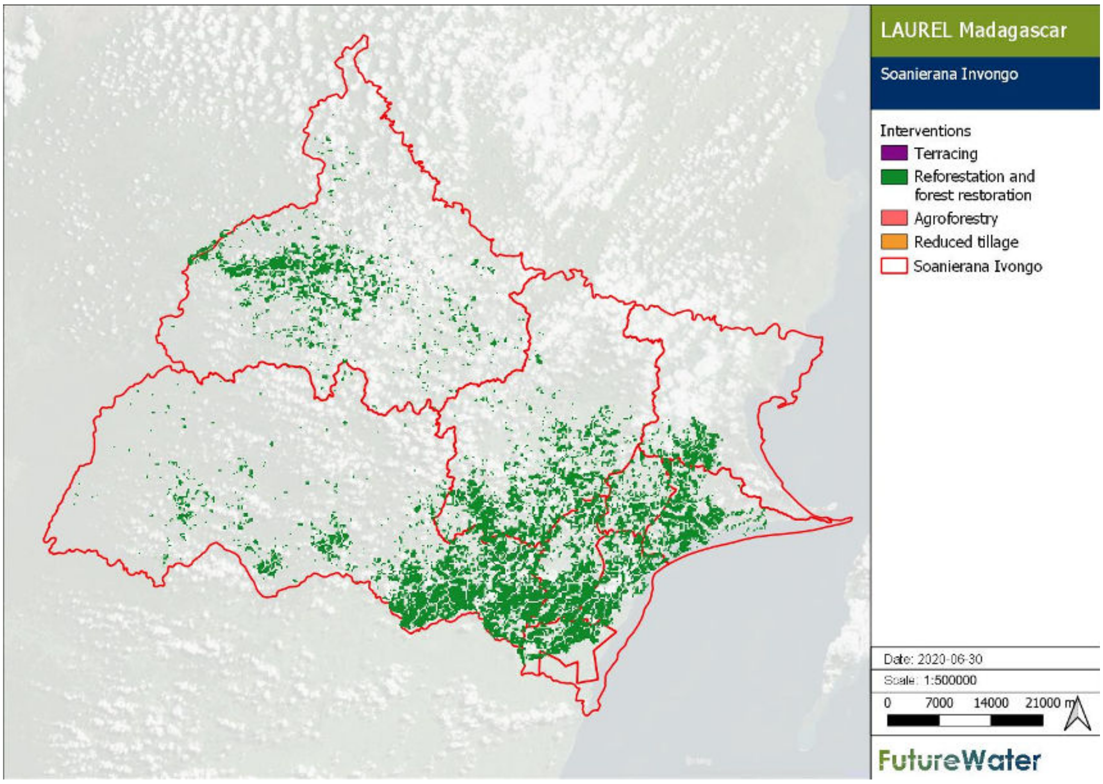


Figure 6. Interventions simulated for Soanierana Ivongo

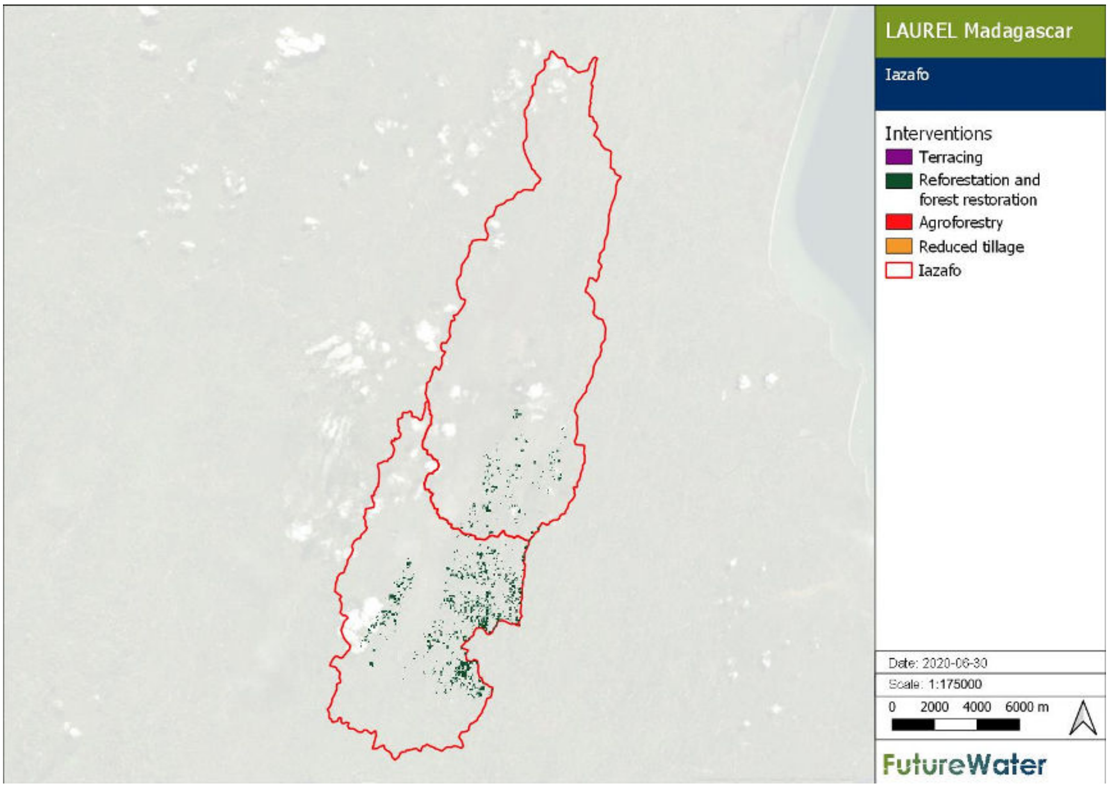


Figure 7. Interventions simulated for Iazofo.

2.3 Simulation of PAGDP Plans for Marovoay and Bealanana

Based on the full intervention scenario results, it is possible to identify the locations where the different interventions are likely to have the greatest beneficial impact. For Marovoay and Bealanana, a scenario was developed which applies the interventions and their respective surface areas as listed in the PAGDP plans to the sites identified in the full intervention runs. The outcome of this is an analysis of the impact of a realistic investment package of PADAP measures on the LAUREL strategic variables, including downstream sediment yield and streamflow.

For determining the beneficial impact and (after economic analyses additional to LANDSIM-R) return on investment of the PADAP measures, it is appropriate to use a Business as Usual (BaU) land use scenario as reference. This accounts for the fact that long-term future impact is targeted, on a time scale when current (2015) land use and management is not representative of conditions without PADAP interventions (BaU). The year 2035 was selected as a suitable time horizon for this analysis. The 2035 land use maps used in these BaU simulations for Marovoay and Bealanana, as produced by the national model that is part of LANDSIM-P, are shown in Figure 8 and Figure 9, and compared to the 2015 baseline land use maps.

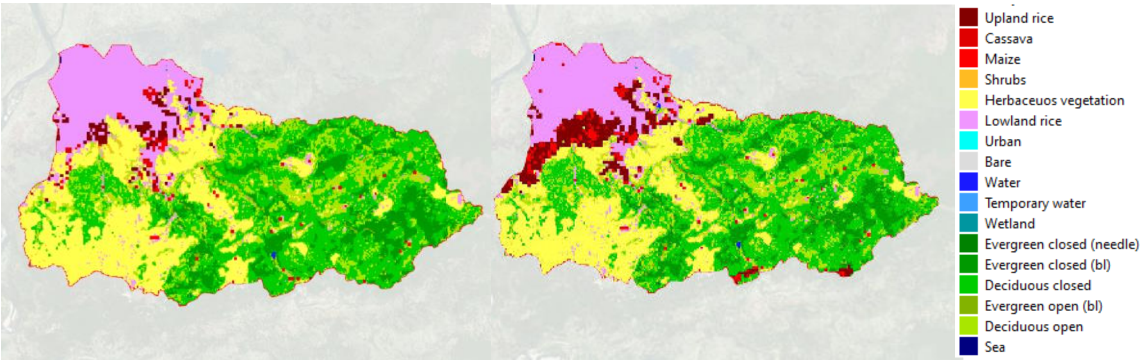


Figure 8. Land use changes in Marovoay predicted by the national model of LANDSIM-P: 2015 (left) vs. 2035 (right).

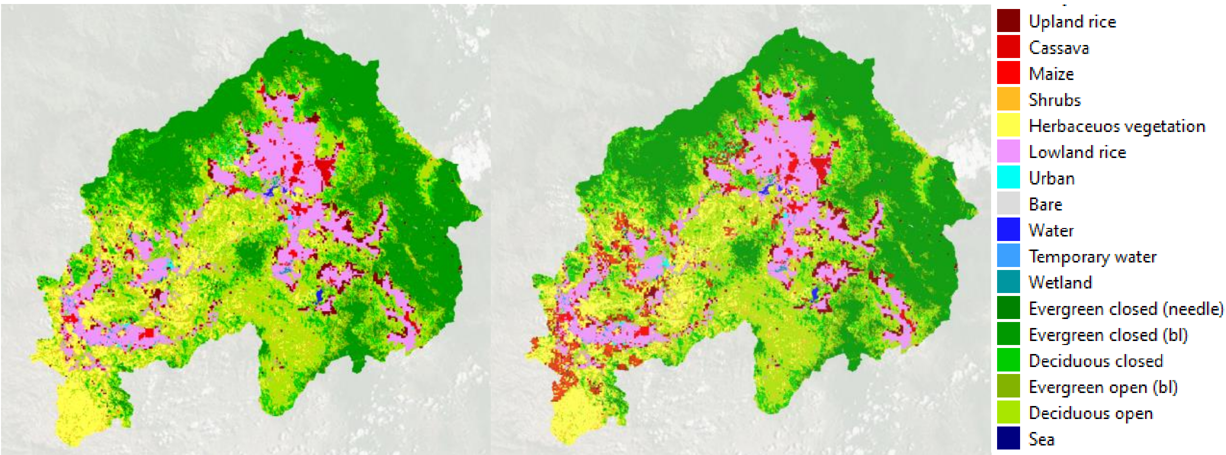


Figure 9. Land use changes in Bealanana predicted by the national model of LANDSIM-P: 2015 (left) vs. 2035 (right).

Based on the results of the full interventions scenarios, both for Marovoay and Bealanana, the most suitable interventions areas are spatialized according to the surface areas mentioned in Table 1 and Table 2. Given the fact that the full intervention scenarios show scattered patterns throughout the catchment, and measures are more likely to be implemented in clusters in reality, the intervention packages were selected according to the following rules:

<u>Marovoay</u>

- Reforestation: minimum of 2 ha (minimum of 2 connected pixels)
- Reduced tillage: minimum of 20 ha

<u>Bealanana</u>

- Reforestation: minimum of 4.5 ha (minimum of 2 connected pixels)
    - except for the SP Bealanana area, where single pixels were selected to reach 150 ha
- Agroforestry: not implemented in the model because of the small area mentioned in Table 2 (10 ha per sub-catchment). This equals only 4 pixels and will not provide any significant downstream impacts. However, local on-site effects maybe desirable, but these are already simulated in the full intervention runs.

Small adaptions to the model were implemented because a first analysis showed that the impact of interventions, especially during wet years, were not as expected with increased erosion rates. The following adaptions were implemented:

- Root depth of open forest decreased from 2000 mm to 1500 mm
- Runoff coefficient (Manning) of closed forest increased from 0.2 to 0.3

Both adaptations were implemented to increase the difference between the landuse classes of open and closed forest (there was no significant difference between the two landuse classes its corresponding input parameters). Especially reforestation is often implemented in the currently degraded (open) forest land use areas which should have a positive impact on erosion rates end sediment transport.

3 Results

3.1 Identifying suitable sites for SLM interventions

The paragraphs below show the results of the “full intervention” scenarios for the different areas. For each area, two maps are presented:

1. A map with the erosion rate (t/ha) for the current situation (baseline run);
2. A map with the erosion reduction rate (t/ha) after the full interventions.

The maps only show the results for areas outside streams and river beds (sites with a drainage area of < 1 km^2), as these are the locations where the selected interventions could be implemented in reality. Erosion reduction is also presented in a table for every sub-catchment in each area. For each intervention, the area (ha) erosion (t and t/ha) and erosion reduction (t) is calculated. These tables are useful to select the sub catchments where the highest impact of interventions can be expected.

The impact of some of the interventions reaches further than only the area (grid cells) where the interventions are implemented. This is especially relevant for interventions relating to reforestation and agroforestry, where decreased fast runoff also affects the area directly downstream, as can be clearly seen on the maps. In the tables however, only the impact of the interventions in the area of implementation is presented, in order to allow for assessment and comparison of erosion reduction caused by each specific intervention.

3.1.1 Marovoay

Figure 10 shows the average annual erosion rate in t/ha in Marovoay. The highest erosion rates are observed in the lower south west, middle west and lower east (sub catchments SP 1, SP 2, SP 5 and SP 6). Erosion rates in these areas can reach around 20-40 t/ha but can even exceed these numbers.

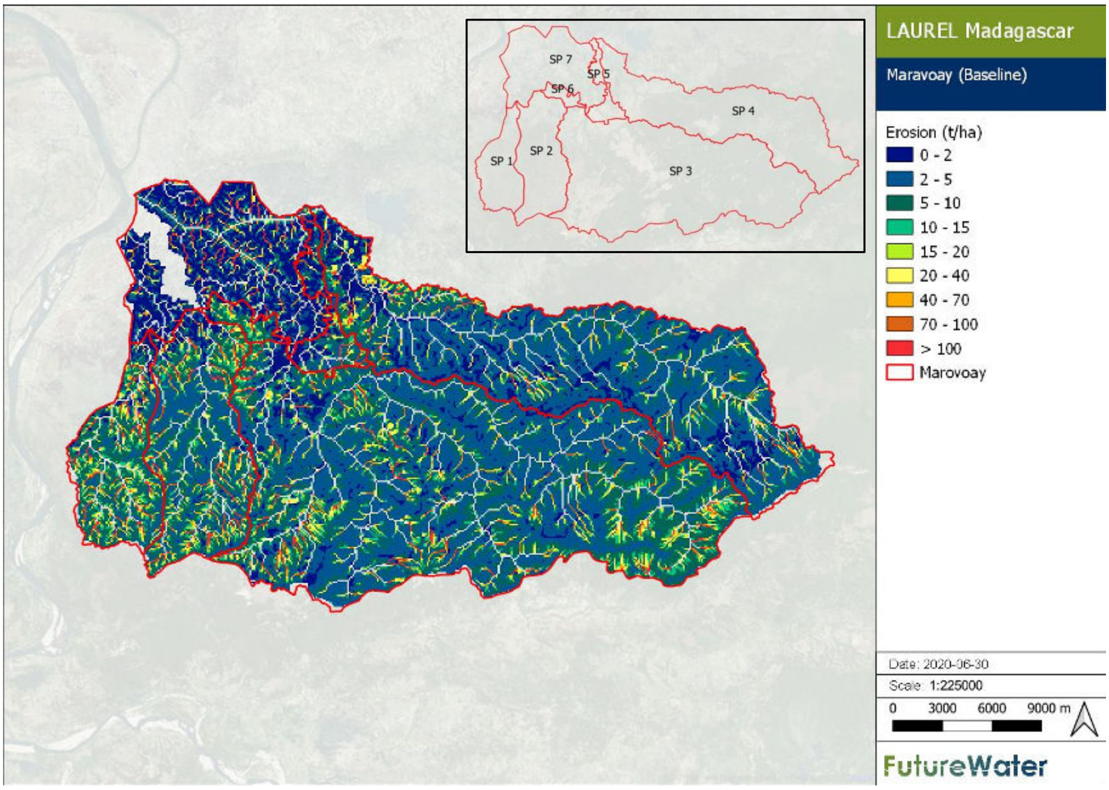


Figure 10. Average annual soil erosion rate (t/ha) in Marovoay.

Figure 11 shows the erosion reduction that is achieved after implementation of the full interventions. Especially in and around sub catchment SP 5, the erosion reduction is significant.

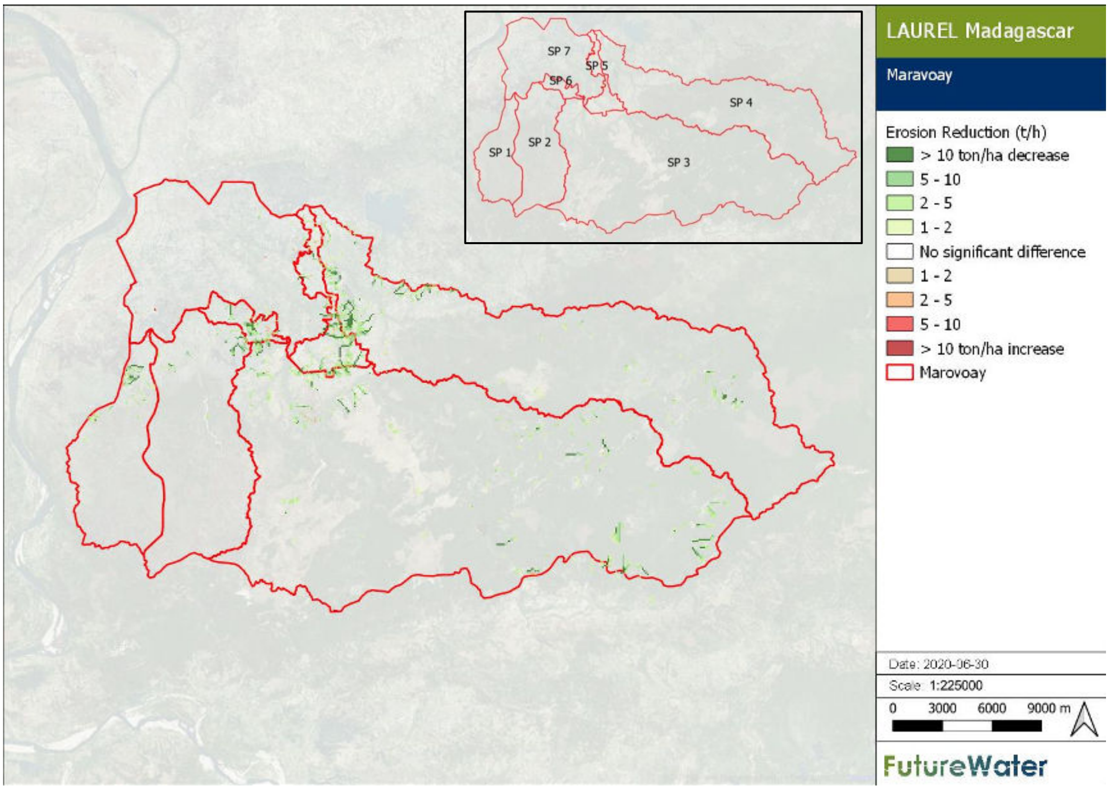


Figure 11. Annual erosion reduction (t/ha) in Marovoay after the interventions.

Table 7 shows the impact of the different interventions in every sub-catchment. Especially the reforestation appears to have a high impact on erosion rates, with a reduction in erosion rate ranging between 13% and 52%. Reduced tillage appears to be somewhat less effective, with decreases of erosion rates between 3 – 20%. It should be noted that, as mentioned earlier, reduced tillage is often applied in combination with other conservation agriculture practices, which is likely to enhance the reduction rate in these areas. Another important factor here is that the typical timing of tillage is after the main peaks in rainfall (and thus, soil erosion).

Table 7. Impact of interventions on erosion reduction in every sub catchment in Marovoay

Sub catch-ment	Area (ha)	Erosion (t)	Erosion (t/ha)	Erosion Reduction (t)	Erosion Reduction (%)	Area (ha)	Erosion (t)	Erosion (t/ha)	Erosion Reduction (t)	Erosion Reduction (%)
	Reforestation					Reduced Tillage				
SP 1	40	361	9	125	35	82	1582	19	53	3
SP 2	31	1445	47	758	52	40	306	8	16	5
SP 3	1384	12224	9	1598	13	571	15341	27	1103	7
SP 4	990	7020	7	1104	16	96	1149	12	227	20
SP 5	131	1252	10	569	45	-	-	-	-	
SP 6	65	703	11	308	44	-	-	-	-	
SP 7	7	9	1	-15		-	-	-	-	

3.1.2 Bealanana

Figure 12 shows the average erosion rate in t/ha in Bealanana. The highest erosion rates are observed in the eastern sub catchments of Ambatoriha and Marotolana (1 and 3). The annual average erosion rates in these areas can locally exceed 20-40 t/ha.

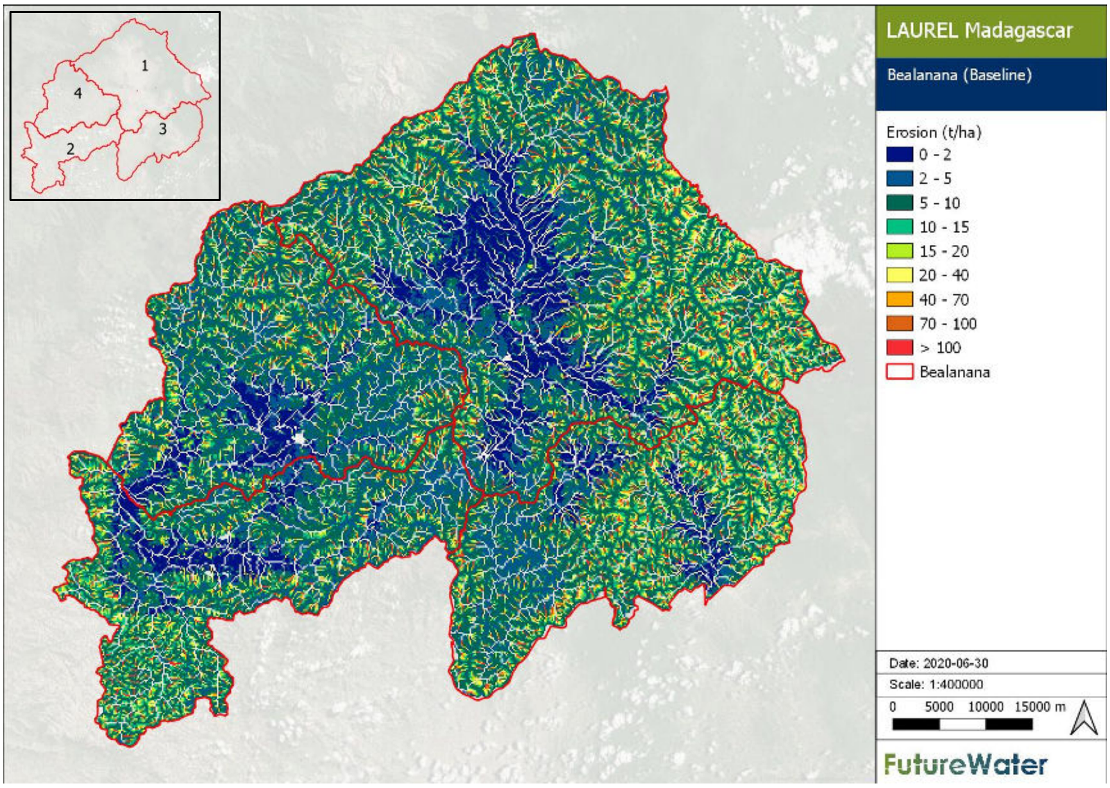


Figure 12. Average annual soil erosion rate (t/ha) in Bealanana.

Figure 13 shows the erosion reduction that was achieved after implementation of the interventions. Erosion reduction rates are in general somewhat lower than in Marovoay, with a typical range of 2 – 5 t/ha. Particularly on specific locations in the western Marotolana and Bealanana subcatchments, interventions are expected to have a higher impact. The overall limited impact of reforestation can be explained by the fact that this intervention is quite scattered throughout the catchment. Such a spatial arrangement of interventions will in practice not be very realistic, and further consultation with the PADAP team will be held before simulating the actual PADAP intervention package and its downstream impacts (see Section 2.3).

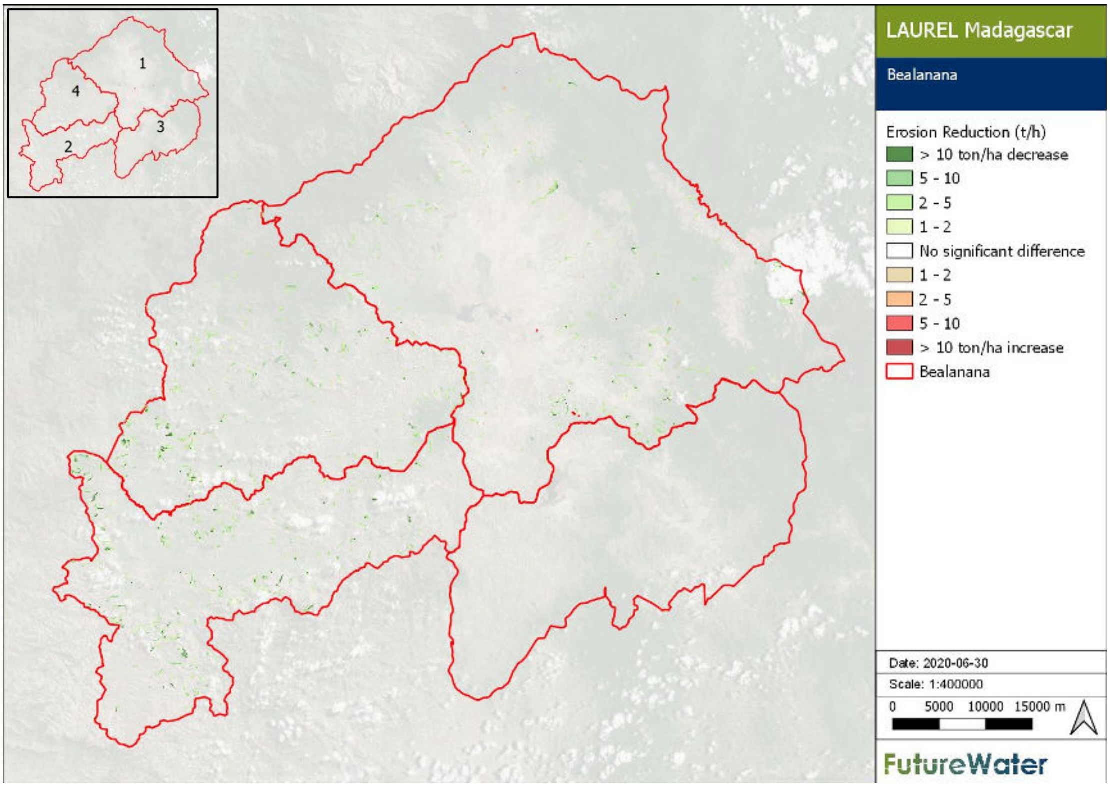


Figure 13. Annual erosion reduction (t/ha) in Bealanana after the interventions.

Table 8 shows the impact of the different interventions for each sub-catchment in Bealanana. The total area that is reforested is higher than the area which is simulated for agroforestry, but agroforestry overall appears to have more impact. Again, the clustering of agroforestry clearly has a beneficial impact.

Table 8. Impact of interventions on erosion reduction in every sub-catchment in Bealanana.

Sub catchment	Area (ha)	Erosion (t)	Erosion (t/ha)	Erosion Reduction (t)	Erosion Reduction (%)	Area (ha)	Erosion (t)	Erosion (t/ha)	Erosion Reduction (t)	Erosion Reduction (%)
	Reforestation					Agroforestry				
1 - Ambatoriha	778	5683	16	336	6	466	10745	52	1777	17
2 - Marotolana	792	6182	18	1702	28	488	9402	43	1919	20
3 - Ambatosia	-	-	-	-	-	-	-	-	-	-
4 - Bealanana	650	3848	13	291	8	652	8860	31	1703	19

3.1.3 Andapa

Figure 14 shows the average erosion rate in t/ha in Andapa. Erosion rates in Andapa are generally quite high with some hotspots topping 100 t/ha, especially where barren land coincides with high slopes. For Andapa, two intervention scenarios were developed, one with a focus on reforestation complemented with agroforestry (Agroforestry scenario) while the second one complements reforestation with terracing (Terracing scenario).

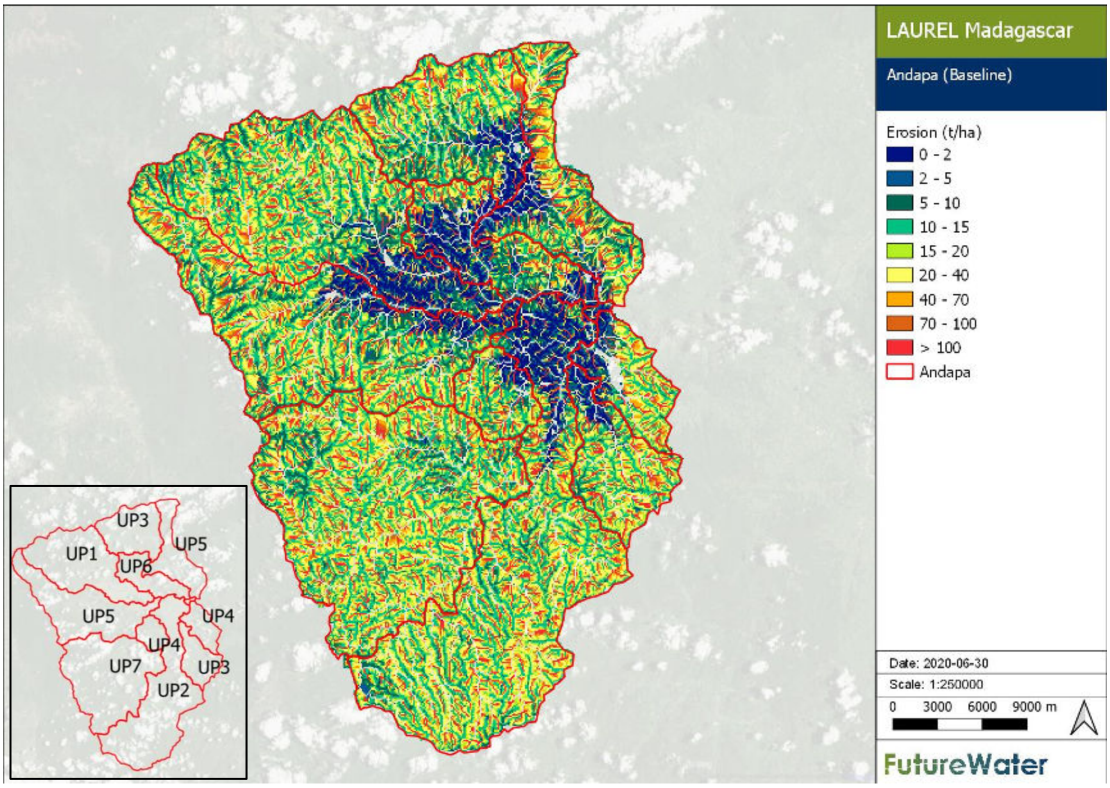


Figure 14. Average annual soil erosion rate (t/ha) in Andapa.

<u>Agroforestry scenario</u>

Figure 15 shows the erosion reduction that can be achieved after implementation of "full" reforestation and agroforestry in Andapa. Most interventions were implemented in regions surrounding agricultural areas. Erosion reductions rates can be significant. In some areas the reduction rates can be higher than 10 t/ha.

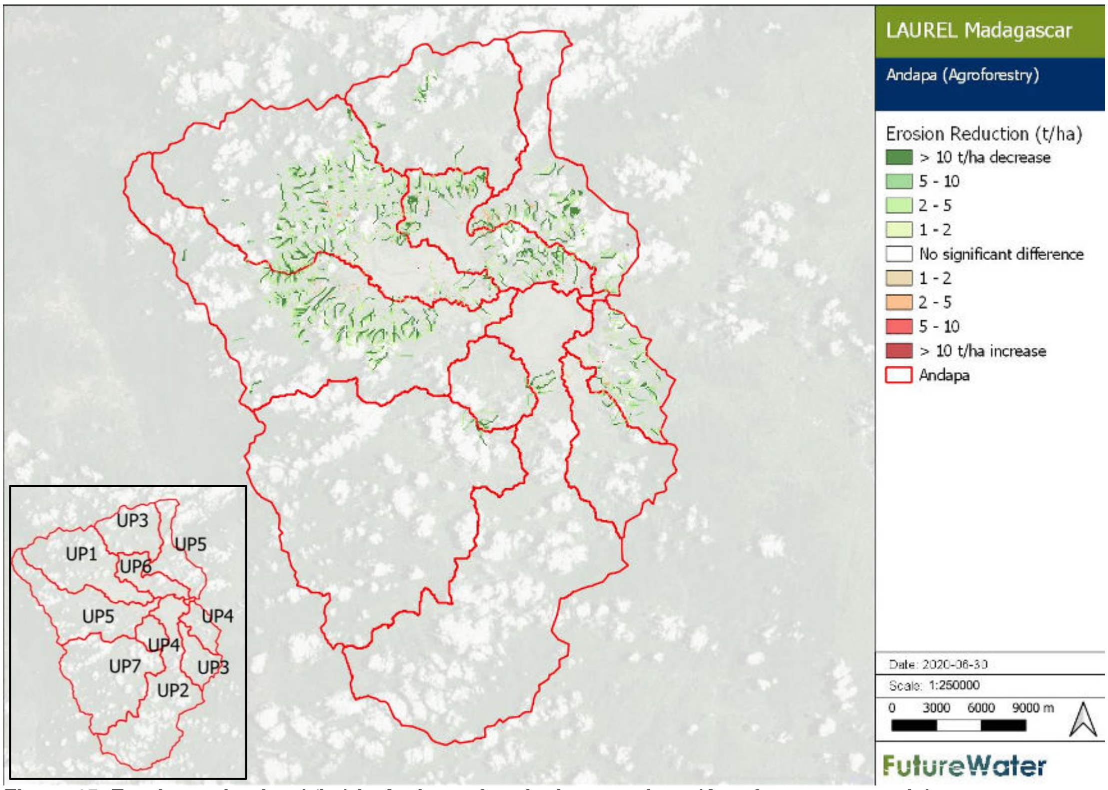


Figure 15. Erosion reduction (t/ha) in Andapa after the interventions (Agroforestry scenario).

Table 9 shows the impact of the different interventions in every sub catchment in Andapa according to the Agroforestry Scenario. Reforestation is effective, especially in the areas where quite some area is reforested (UP 4 (east), UP 5's and UP 6). It yields erosion reduction rates of 10- 25%. Agroforestry also is an effective measure against soil erosion, also achieving reduction rates of around 20 – 25%. Agroforestry however is implemented on a much smaller scale in some very erosive areas, which means that an intervention can be successful quickly.

Table 9. Impact of interventions on erosion reduction in every sub catchment in Andapa (only results for sub-catchments with >25 ha of interventions are shown).

Sub catchment	Area (ha)	Erosion (t)	Erosion (t/ha)	Erosion Reduction (t)	Erosion Reduction (%)	Area (ha)	Erosion (t)	Erosion (t/ha)	Erosion Reduction (t)	Erosion Reduction (%)
	Reforestation					Agroforestry				
UP 1	1276	55775	44	6740	12	44	10439	237	2676	26
UP 2	-	-	-	-	-	46	2035	44	454	22
UP 3 (north)	83	2549	31	277	11	-	-	-	-	-
UP 4 (centre)	-	-	-	-	-	43	2428	56	481	20
UP 4 (east)	179	6690	37	262	4	27	2067	77	404	20
UP 5 (east)	980	45494	46	5060	11	-	-	-	-	-
UP 5 (west)	350	16312	47	1682	10	80	13358	167	2528	19
UP 6	383	10419	27	2684	26	165	9865	60	1951	20

Terracing

Figure 16 shows the erosion reduction that can be achieved after implementation of reforestation and terracing in Andapa. These interventions seem to yield a similar result as the Agroforestry scenario with substantial erosion reduction rates of over 10 t/ha.

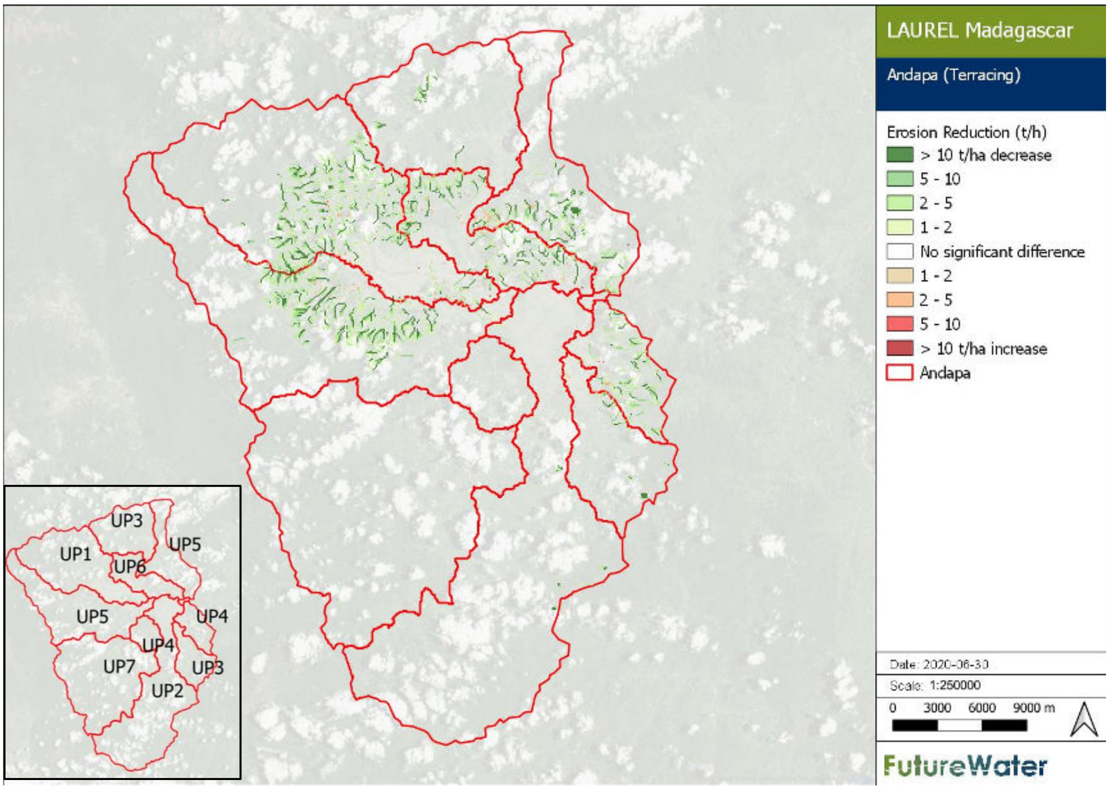


Figure 16. Erosion reduction (t/ha) in Andapa after the interventions (Terracing scenario).

Table 10 shows the impact of terracing in each of the sub-catchments where this intervention is simulated. Terracing is shown to be an effective measure against soil erosion with erosion reduction rates of about 10 -15%. Compared to the agroforestry impact for the same areas, the impact is overall a bit lower.

Table 10. Impact of interventions on erosion reduction in every sub catchment in Andapa (only results for sub-catchments with >25 ha of interventions are shown).

Sub catchment	Area (ha)	Erosion (t)	Erosion (t/ha)	Erosion Reduction (t)	Erosion Reduction (%)
	Terracing				
UP 2	45	3370	75	420	12
UP 3 (south)	36	6206	172	804	13
UP 5 (west)	62	12576	203	1547	12

3.1.4 Soanierana Ivongo

Figure 17 shows the average erosion rate in t/ha in Soanierana Ivongo. Erosion rates in Soanierana Ivongo are on average not very high, due to most of the catchment being forested.

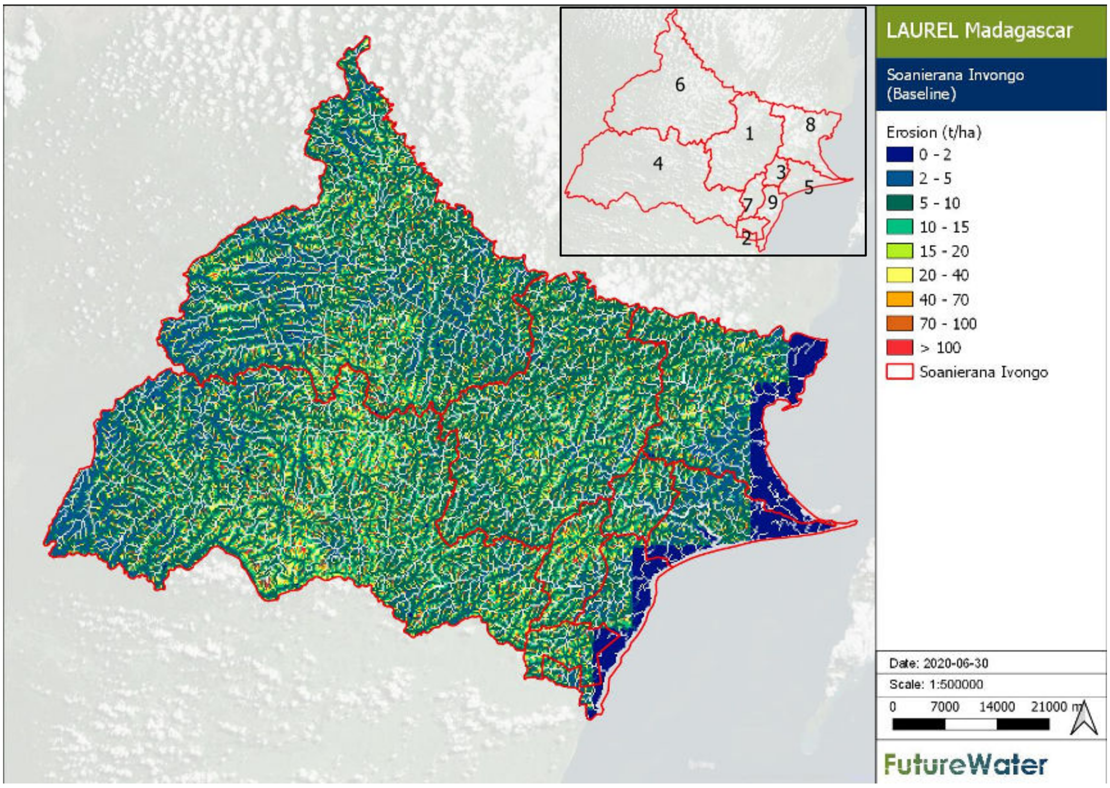


Figure 17. Average annual soil erosion rate (t/ha) in Soanierana Ivongo.

Figure 18 shows the impact of the different interventions in each sub-catchment in Soanierana Ivongo. Although forest restoration and reforestation is implemented in a relatively large area, the impact of the interventions is variable due to e.g. differing terrain slopes and soil properties. However, especially in those communes with higher erosion rates lots of reforestation was implemented, e.g. Andapafito and also Antenina, it is quite a successful measure.

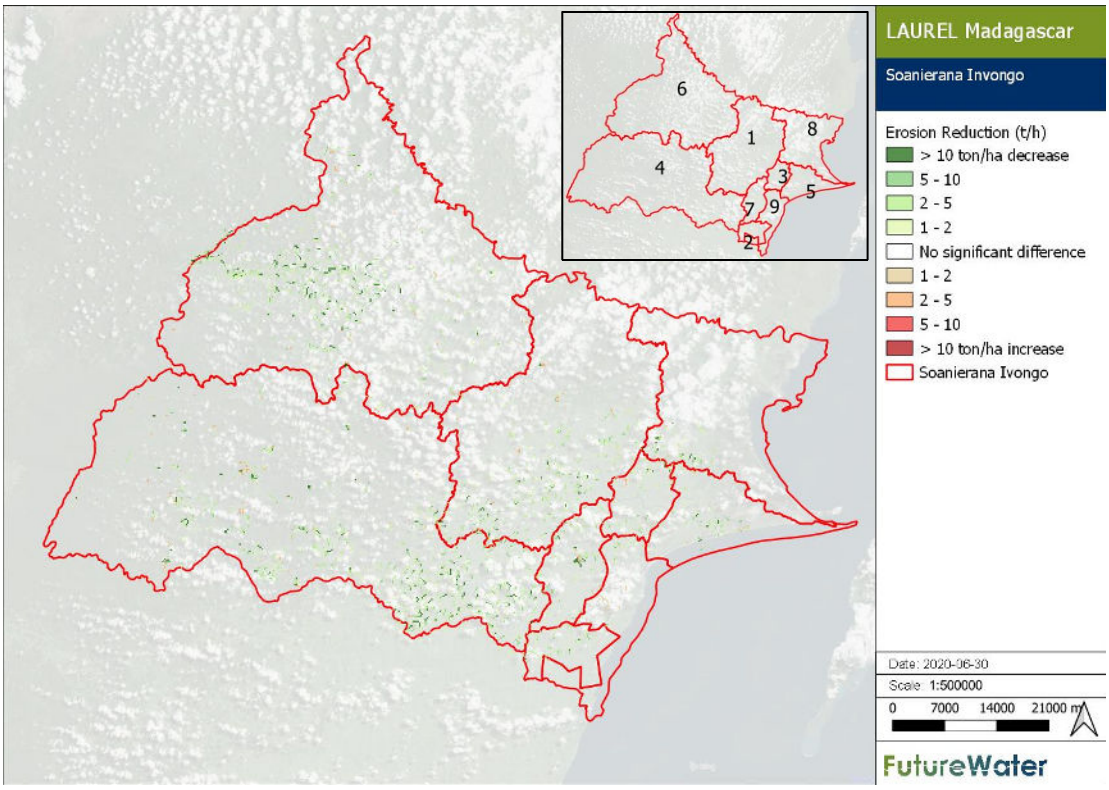


Figure 18. Erosion reduction (t/ha) in Soanierana Ivongo after the interventions.

This is also visible in Table 11, where Andapafito and Antenina show a reduction rate of 11% and 15% respectively. However, results differ quite a lot throughout the different sub-catchments. Probably also because of the already low erosion rates in Soanierana Ivongo, overall the impact of the interventions appears to be more limited than in the other catchments.

Table 11. Impact of interventions on erosion reduction in every sub catchment in Soanierana Ivongo.

Commune	Area (ha)	Erosion (t)	Erosion (t/ha)	Erosion Reduction (t)	Erosion Reduction (%)
			Reforestation		
1 - Ambahoabe	9296	31991	14	1579	5
2 - Ambinanisa	2520	10940	17	358	3
3 - Ambodiampana	2644	10407	16	355	3
4 - Andapafito	17392	69695	16	7726	11
5 - Antanifotsy	4896	11406	9	197	2
6 - Antenina	8936	27705	12	4200	15
7 - Fotsialanana	5168	24183	19	1415	6
8 - Manompana	2200	8420	15	725	9
9 - Soanierana-Ivongo	4000	9692	10	-105	0

3.1.5 Iazafo

Figure 19 shows the erosion rate in Iazafo. There are areas with a very high erosion ratio, even over 100 t/ha. This can be explained by steep hillslopes, degraded land cover, as well as considerably higher rainfall levels compared to Marovoay, Bealanana, and Andapa.

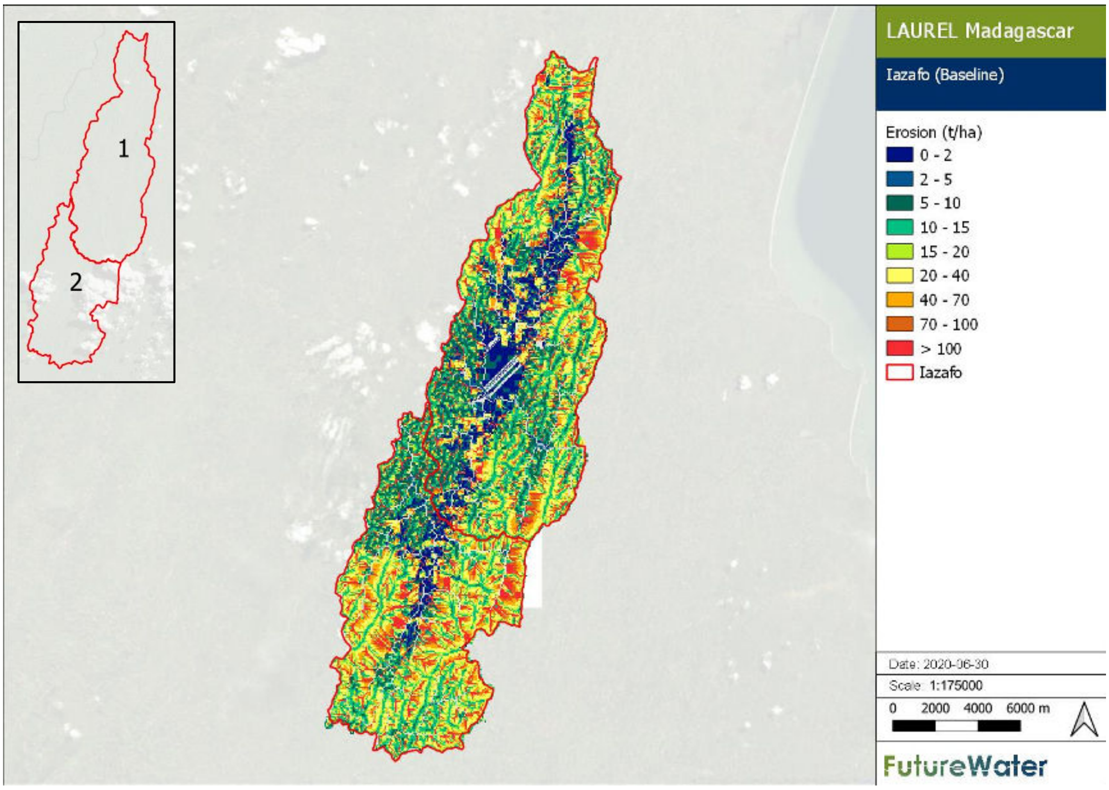


Figure 19. Average annual soil erosion rate (t/ha) in Iazofo.

Figure 20 shows the impact of the interventions in Iazafo. Interventions consisted of reforestation, mainly focussing on the Mananonoka sub catchament (2). These reforestation interventions have positive impact on erosion, with a local decrease of erosion rates that exceed 10 t/ha.

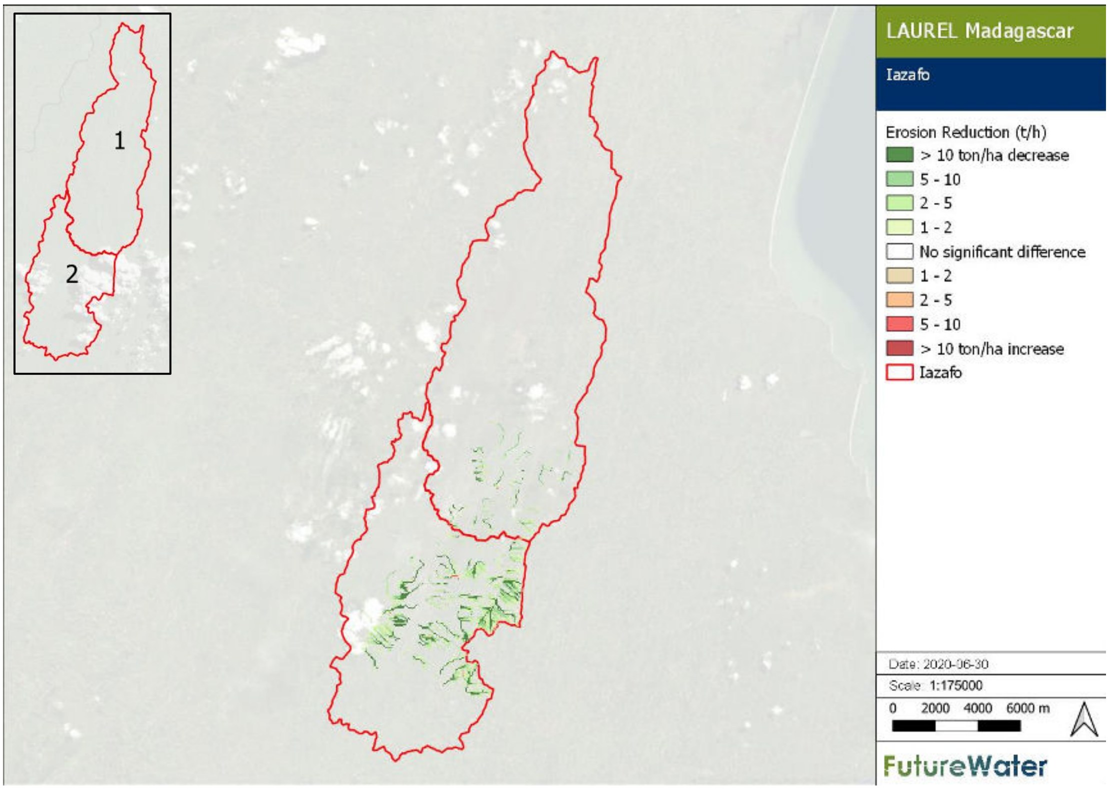


Figure 20. Erosion reduction (t/ha) in Iazofo after the interventions.

Table 12 shows the impact of the reforestation interventions per sub catchment. Especially in the Mananonoka sub catchment, reforestation is successful. The soil erosion can be reduced with almost 20%.

Table 12. Impact of interventions on erosion reduction in every sub catchment in Izafo.

Sub catchment	Area (ha)	Erosion (t)	Erosion (t/ha)	Erosion Reduction (t)	Erosion Reduction (%)
	Reforestation				
1 - Iazofo	70	6663	24	208	3
2 - Mananonoka	364	156304	107	29456	19

3.2 Simulation of PAGDP Plans for Marovoay and Bealanana

3.2.1 Marovoay

Considered interventions for the Marovoay catchment are reforestation (2400 ha) and reduced tillage (150 ha). The is about 3% of the entire Marovoay catchment, and a significant impact, especially on the local scale could be expected.

Figure 21 shows the selected interventions for Marovoay. The selection of interventions was based on the erosion reduction achieved by the full interventions for Marovoay (Figure 11). For the analysis of erosion reduction, 17 locations were selected where several different model output parameters are calculated/registered, most importantly being the discharge and sediment yield. The 17 stations have upstream areas of different sizes in which more or less interventions are implemented, to be able to estimate the impact of the different interventions on different scales and distances (local scale, e.g.

station 15, 16; sub catchment scale, e.g. station 1, 3; and total catchment scale, e.g. station 7). In follow-up LANDSIM-R applications within PADAP, these station locations can be selected based on guidance from the local field teams. They should represent sites where a certain impact on sedimentation and/or water availability is desired.

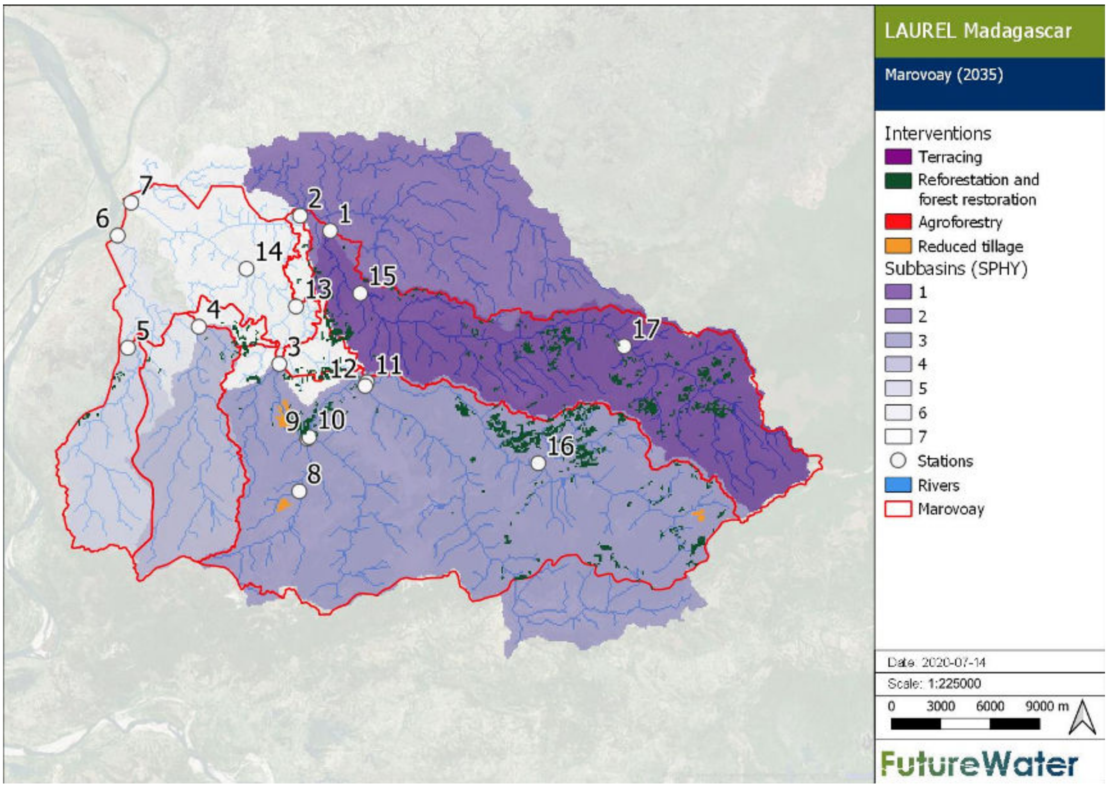


Figure 21. Selected interventions in every subbasin, including the stations where the average monthly sediment yield and discharge is calculated.

3.2.1.1 Erosion reduction on a (sub) catchment scale

Figure 22 shows the impact of the selected interventions in the total Marovoay catchment. The erosion reduction after interventions is clearly visible in the areas surrounding stations 13, 16 and 17, corresponding to areas where most of the interventions are implemented.

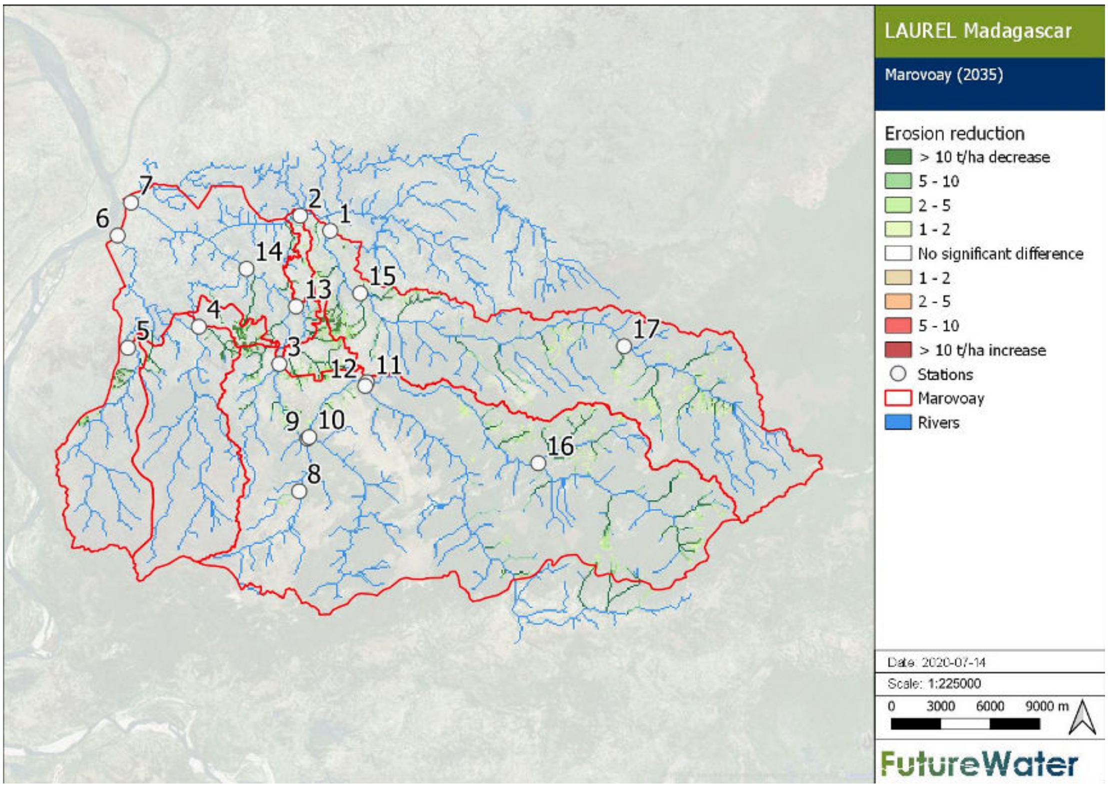
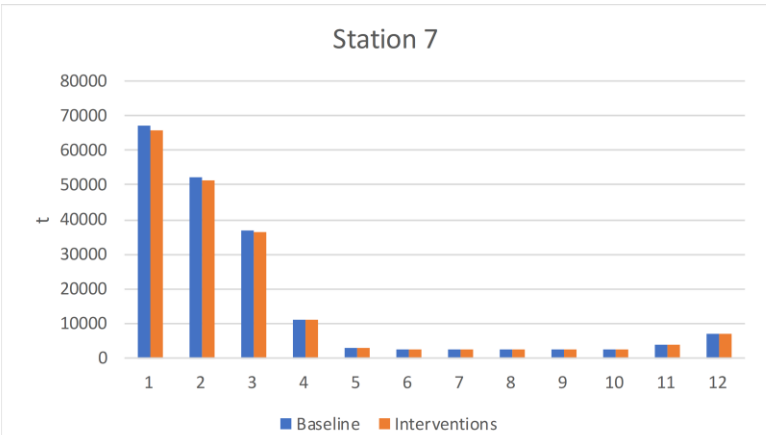


Figure 22. Average annual erosion reduction (t/ha) after the interventions in Marovoay.

Figure 23 shows the monthly sediment yield (in tonnes) and the monthly average sediment yield reduction (%) at station 7. Station 7 is located at the outlet of the catchment, which means that all of the interventions in Marovoay that are implemented are located upstream of this point. With the implementation of the proposed interventions (2400 ha of reforestation and 150 ha with reduced tillage), a total annual erosion reduction of 3017 t can be achieved, which is a percentual reduction of 2%. During the wet months of January, February and March, sediment yield and sediment yield reduction are highest.



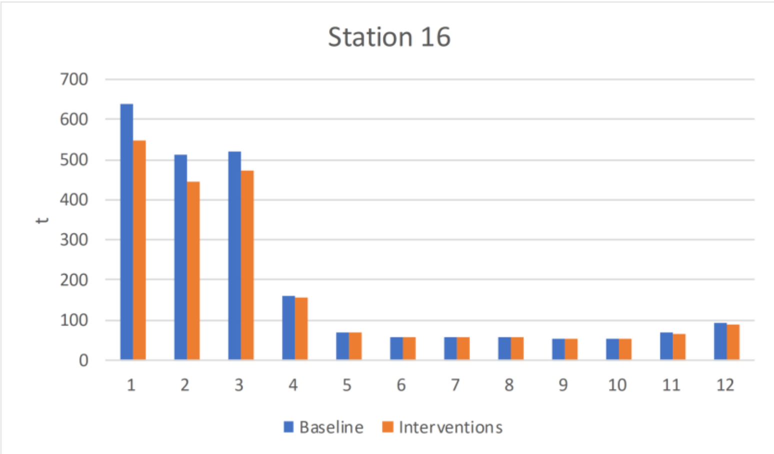
Month	Sediment yield reduction
January	-2%
February	-2%
March	-1%
April	-1%
May	0%
June	-1%
July	-1%
August	-1%
September	-1%
October	-1%
November	-1%
December	-1%

Figure 23. Average annual sediment yield (t) (left) at station 7 and average monthly reduction after interventions (right).

Although an erosion reduction of 2% seems rather limited, the interventions can result in significant sediment yield reductions on a local scale.

3.2.1.2 Erosion reduction on a local scale

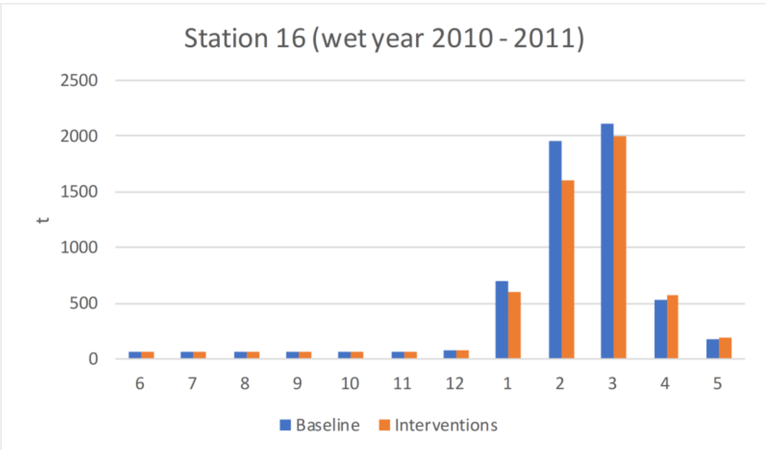
Figure 24 shows the monthly sediment yield (in t) and the monthly average erosion reduction (%) at station 16. Station 16 is located just downstream of an area where reforestation is implemented. Reforestation yields, especially during the wet season a high sediment yield reduction of almost 15% in January, which is on average the wettest month the highest erosion rate. The yearly average amount of sediment yield at station 16 is 2342 t, which is reduced by the interventions with 223 t, a reduction of 10%.



Month	Sediment yield reduction
January	-14%
February	-13%
March	-9%
April	-3%
May	-1%
June	-1%
July	-1%
August	-1%
September	-1%
October	-1%
November	-5%
December	-6%

Figure 24. Average annual sediment yield (t) (left) at station 16 and average monthly reduction after interventions (right).

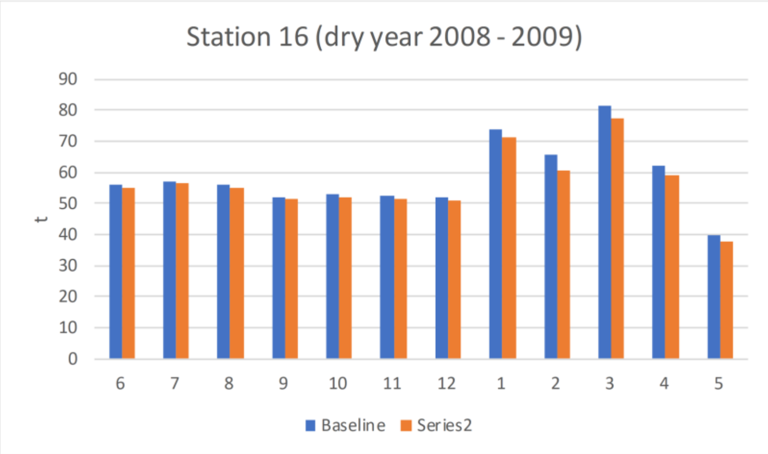
During a wet year (for example June 2010 – May 2011), the interventions even have a bigger impact compared to the average situation (Figure 25). In wet years especially, erosion can be significantly higher due to increased surface runoff. Interventions should therefore especially be effective in these years. Figure 25 shows that during the wet months, i.e. January, February and March, erosion is significantly reduced. After reforestation, the soil is better capable of storing water which reduces the rainfall runoff component with 14 to 18% in January and February. The slight increase in erosion in April and May is caused by an increase in rainfall runoff in these months, probably due to fact that the soils are still saturated with water. The total erosion reduction achieved after interventions for a wet year similar to 2010 – 2011 is 519 t, which is 9% of the total sediment yield in this wet year, but it is 22% of the sediment yield of an average year (2342 t).



Month	Sediment yield reduction
June	-3%
July	-2%
August	-1%
September	-1%
October	-1%
November	-1%
December	-3%
January	-14%
February	-18%
March	-5%
April	7%
May	7%

Figure 25. Average monthly sediment yield (t) (left) at station 16 and average monthly reduction after interventions (right) in a wet year (June 2010 – May 2011).

During a dry year (for example June 2008 – May 2009), the impact of the interventions in the wet months is slightly lower, between 3% and 8%. However, there is no increase in sediment yield in April and May which imply that the interventions have a positive impact on the storage capacity of the soil. The total erosion reduction achieved after interventions in a dry year is 24 t, comparable to about 3% of the total sediment yield during a dry year (701 t).



Month	Sediment yield reduction
June	-1%
July	-1%
August	-2%
September	-2%
October	-2%
November	-2%
December	-2%
January	-3%
February	-8%
March	-5%
April	-5%
May	-6%

Figure 26. Average monthly sediment yield (t) (left) at station 16 and average monthly reduction after interventions (right) in a dry year (June 2008 – May 2009).

3.2.1.3 Erosion reduction during extreme events

Especially during intense rainfall events or longer wetter periods with saturated soils and high discharges in the rivers, erosion and sediment transport can be significant. It is therefore important to also analyze the sediment yield of extreme events, which are known to produce the largest hazardous amounts of sediments. The first months of the year 2011 were quite wet, with a cumulative precipitation amount of almost 1500 mm from January 1st until the 25th of March measured at station 16. On the other hand, the average cumulative precipitation between 2005 and 2015 is 1070 mm, which is 40% less than the cumulative precipitation of 2011. Figure 27 shows the daily and cumulative precipitation at station 16 for the beginning of 2011 and the average between 2005 and 2015. This graph clearly shows that this period was much wetter than average with some very intense rainfall events.

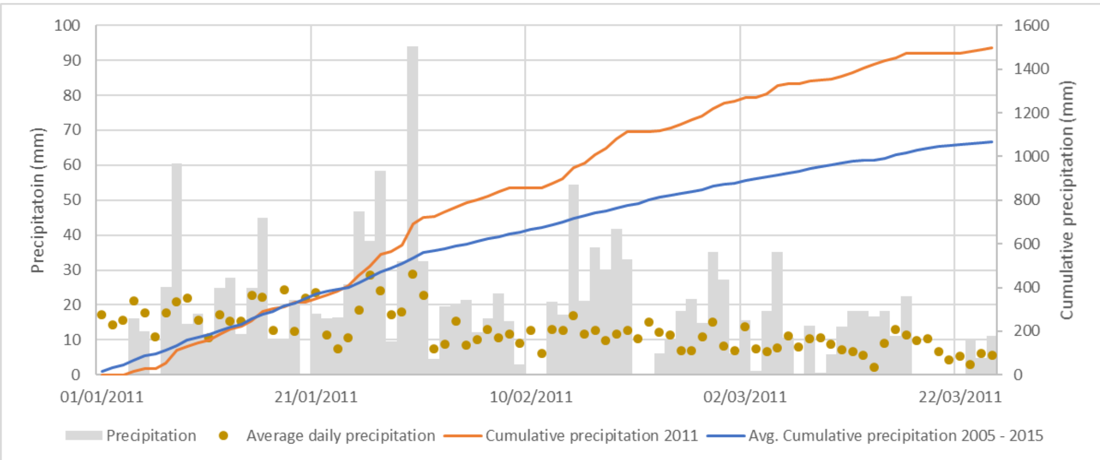


Figure 27. Daily and cumulative precipitation for the first months of 2011 and for the average over 2005 – 2015 at station 16.

As a result of this wet period, sediment yield was also significantly higher than average. Figure 28 shows the impact of the interventions on the daily sediment yield. It is clearly visible that the interventions significantly reduce the sediment yield during this wet period, with a maximum reduction of 25% and an average reduction of 13% over the entire period.

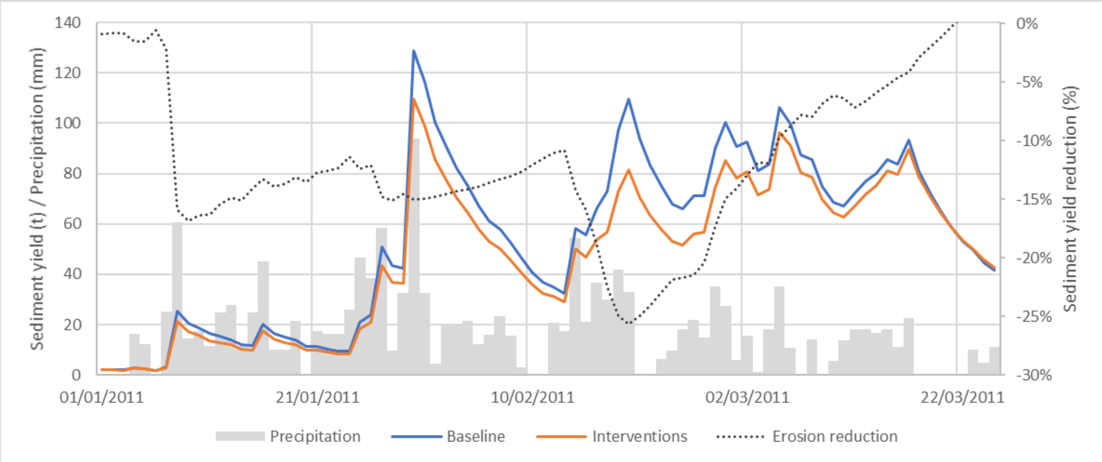


Figure 28. Daily sediment yield (t) and precipitation (mm) at station 16 and sediment yield reduction as a result of the interventions.

3.2.2 Bealanana

Relevant interventions for the Bealanana catchment are reforestation (490 ha) and agroforestry (30 ha). Figure 29 shows the selected interventions for Bealanana. The selection of interventions was based on the erosion reduction achieved by the full interventions for Bealanana (Figure 12). Because of the scattered nature of the full interventions, the impact of the interventions was very limited. Although the selected interventions are selected based on minimum surface area of 4.5 ha (2 grid cells), the selected interventions are still quite scattered throughout the three sub catchments. The surface area of all interventions combined, is also quite small compared to the size of the three sub catchments, 0.17%.

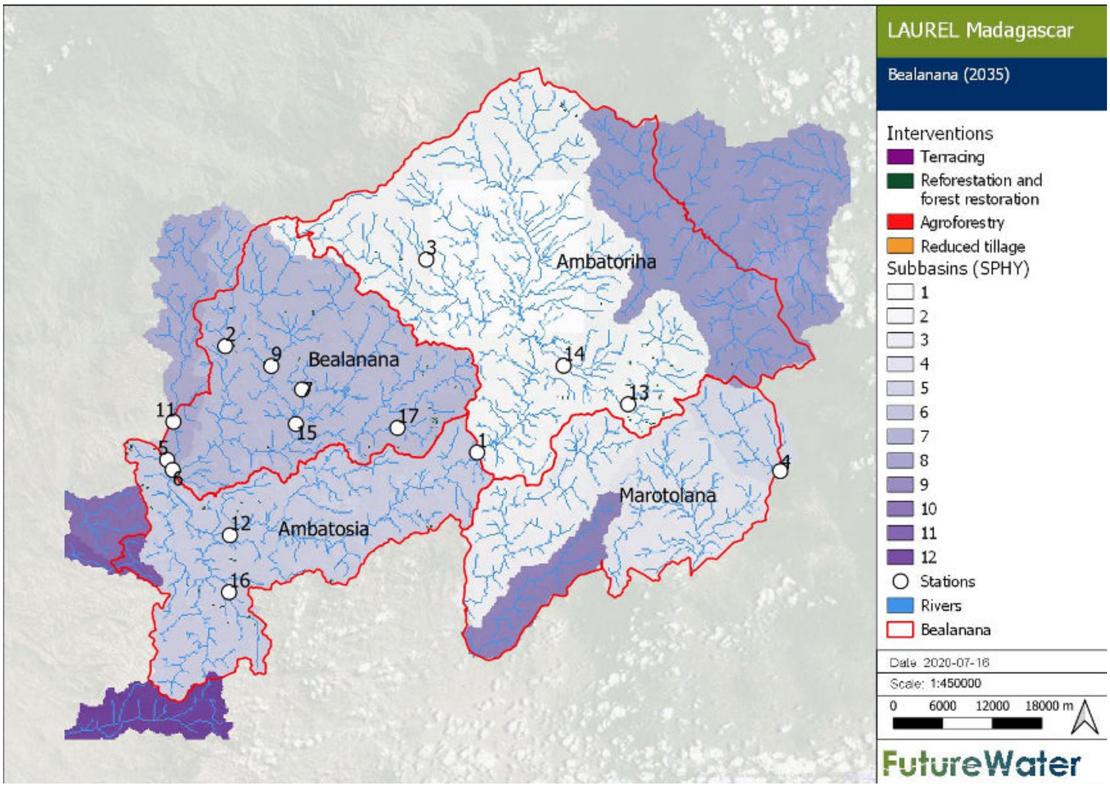


Figure 29. Selected interventions in Bealanana in its subbasins, including the stations where the average monthly sediment yield and discharge is calculated.

3.2.2.1 Erosion reduction on a (sub) catchment scale

Figure 30 shows the impact of the selected interventions in the Bealanana catchment. On a (sub) catchment scale, because of the limited surface area of the interventions, the impact is also very limited. On a local scale, more impact may be expected, for example at station 17.

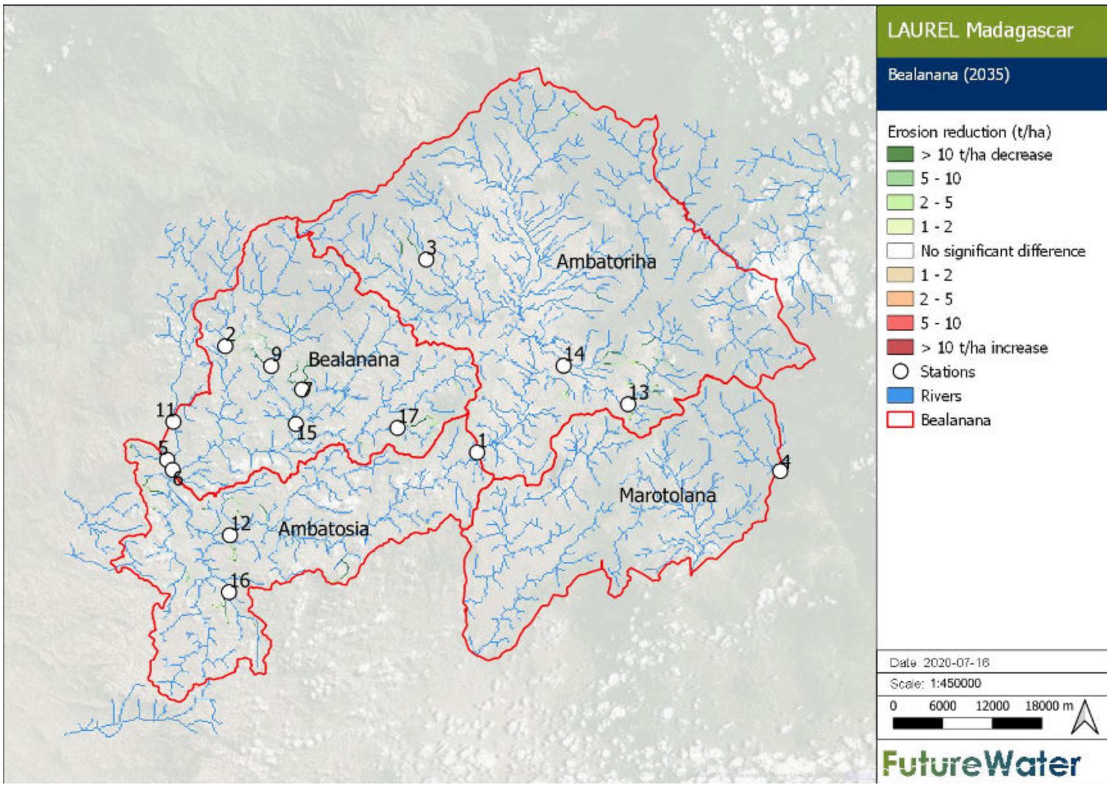
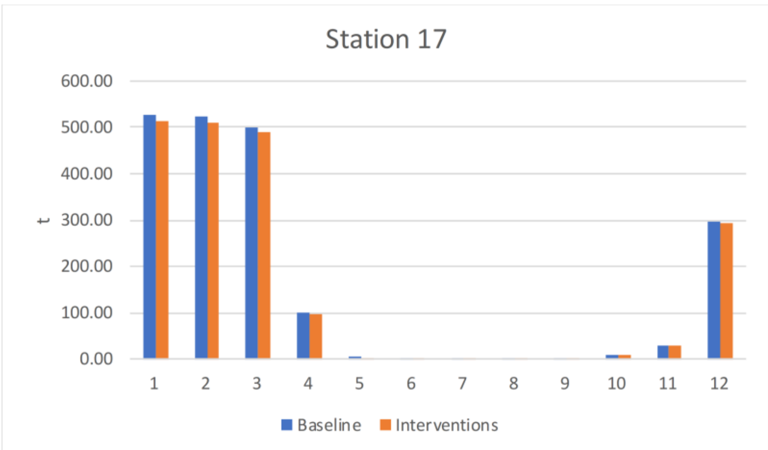


Figure 30. Average annual erosion reduction (t/ha) after the interventions in Marovoay.

3.2.2.2 Erosion reduction on a local scale

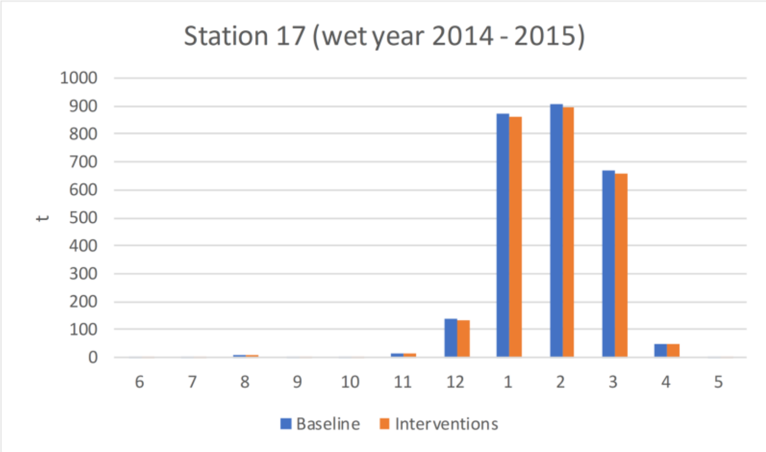
Figure 31 shows the monthly sediment yield (in t) and the monthly average sediment yield reduction (%) at station 17 in the Bealanana SP. Station 17 is located just downstream of an area where reforestation is implemented (45 ha in an area of about 2760 ha). The average annual sediment yield reduction is 41 t, which compares to 2% the total average annual sediment yield at station 17.



Month	Sediment yield reduction
January	-2%
February	-2%
March	-2%
April	-2%
May	-3%
June	-3%
July	-1%
August	-3%
September	-2%
October	-2%
November	-2%
December	-2%

Figure 31. Average annual sediment yield (t) (left) at station 17 and average monthly reduction after interventions (right).

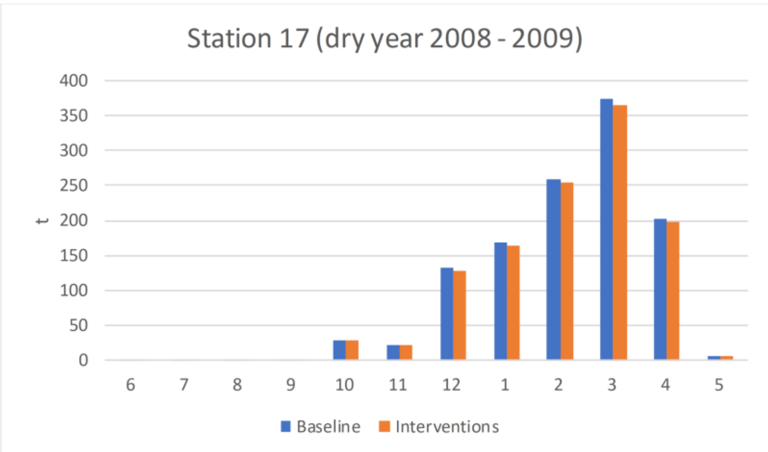
During a wet year (for example June 2014 – May 2015), the interventions have a similar to slightly bigger impact compared to the average situation (Figure 32). The total sediment yield reduction achieved by the interventions is 50 t which is also 2% of the total sediment yield. However, this 50 t is 25% more than the sediment yield reduction in an average year.



Month	Sediment yield reduction
June	-5%
July	-5%
August	-3%
September	-3%
October	-4%
November	-3%
December	-3%
January	-2%
February	-2%
March	-2%
April	-3%
May	-4%

Figure 32. Average monthly sediment yield (t) (left) at station 16 and average monthly reduction after interventions (right) in a wet year (June 2010 – May 2011).

During a dry year (for example June 2008 – May 2009), the impact of the interventions is also comparable to the average. The total erosion reduction achieved by the interventions is 29 t which is also 2% of the total sediment yield in this period.



Month	Sediment yield reduction
June	0%
July	3%
August	3%
September	3%
October	-2%
November	-2%
December	-3%
January	-2%
February	-2%
March	-3%
April	-3%
May	-3%

Figure 33. Average monthly sediment yield (t) (left) at station 16 and average monthly reduction after interventions (right) in a dry year (June 2008 – May 2009).

Overall, the relatively low surface area of the interventions in Bealanana causes a limited impact on sediment yield and hydrology. However, as also observed in Marovoay, the impact of interventions is related in a non-linear way to the sizes of clusters of interventions. The simulated PAGDP package for reforestation consists of a number of sites. In case the surface area of 490 ha of reforestation is the maximum that can achieved for practical or financial reasons, it may be recommended to concentrate all of this reforestation in 1 or 2 sites, to reduce erosion on those sites where it is most harmful, or to reduce sediment inflow into a specific location (such as a reservoir or part of an irrigation scheme).

4 Conclusions and recommendations

This report describes the successful application of the LANDSIM-R prototype, as developed under the LAUREL project, to simulate SLM interventions outlined in the PAGDP plans for the PADAP focus catchments. Erosion hotspots were identified for each of the five landscapes and the potential erosion reduction achieved by each of the SLM interventions considered was calculated. The resulting maps and quantitative data are suitable for use in the implementation phase of PADAP, along with other influential factors regarding intervention locations such as differences in costing, logistics, socio-political issues, etc.

For Marovoay and Bealanana, based on the baseline LANDSIM-R runs and the PAGDP plans, the foreseen investments were spatialized and simulated with the model to evaluate their downstream impacts. It was found that the impact of the interventions on the catchment scale is rather limited, but on a local scale, the impact can be very significant. This is highly related to the proportional area of interventions in the upstream area. Especially during the wet season or intense rainfall events, the interventions can greatly reduce erosion and sediment yield, especially in the Marovoay catchment. However, it is of great importance to select the locations for interventions wisely, because otherwise the impact of the interventions is negligible. The results for Bealanana show that scattering interventions in small patches throughout (sub) catchments is not very efficient and will not yield large sediment yield reductions. Converting this information to economic benefits (e.g. mitigation of crop yield losses, reduced water shortages), and integrating data on intervention costs, would allow for an assessment of the return on investment of the SLM measures considered.

Given the scope of this activity, the catchment models already created with the current LANDSIM-R prototype under the LAUREL project have been used to perform these analyses. LANDSIM-R has been designed as such, that it is flexible and allows the user to update model input data and parameterization. It is recommended to look closely into the parameterization of the models for future use, because an improved parametrization will also improve reliability of the results of the scenario runs. This particularly concerns sensitive model parameters such as rooting depth of different land cover classes.

Another key factor in determining the outcomes of the presented analysis is the parameterization of the various interventions in the model. Each intervention introduces a modification to a baseline value of a certain parameter, e.g. vegetation height, ground cover, or slope degree. These values have been established in consultation with the PADAP team over the course of the LAUREL project. Over the course of the PADAP program, it is recommended to keep reviewing these assumptions based on additional knowledge produced under the program. Also, it is recommended to explore options for parameterizing additional interventions proposed in the PAGDP plans but currently not part of LANDSIM-R. These could include e.g. *amélioration des paturages naturels (cultures fourragères), gestion et enrichissement (plantation) des raphières, adaptation du calendrier cultural par rapport à la saison*, as well as planned conservation agriculture measures which can complement the reduced tillage simulations presented for Marovoay.

Follow-up capacity building events are currently being discussed to provide further support to the PADAP experts in terms of improving input data, calibration and validation of LANDSIM-R, especially regarding the model parameters mentioned above. The analyses presented in this report will be an important starting point for these activities. Elaborate discussion of the approach and results is foreseen, and the training will include in-depth analyses of downstream impacts for the three remaining landscapes Andapa, Soanierana Ivongo, and Andapa.