Contribution to Sediment Management at the Drin river hydropower cascade, Albania

N. Efthymiou; P. Schäfer; H. Hildebrand; S. Palt
Fichtner GmbH & Co. KG
PO Box 10 1454
Stuttgart
Germany

F. Bundo
Albanian Power Corporation, KESH SH.A.
Blloku "Vasil Shanto", Rruga "Viktor Eftimiu"
Tirana
Albania

Introduction

The Drin River Cascade comprises three storage hydropower plants under KESH management with 1350 MW total installed capacity. The cascade produces, on an annual average, approximately 70% of the electricity of the country. The hydrological and hydraulic modelling of the river basin and the reservoirs indicated that the spillways of Fierza and Komani lack capacity for safely discharging the PMF, and that the situation will deteriorate in the future due to progressive sedimentation of the reservoirs' active storage. Presently, additional spillways are planned for Fierza and Komani reservoirs.

The implementation of sediment management can slow down or even stop the currently observed storage loss, providing thus the operators with more sustainable flood retention capacities which in turn flatten the outflow hydrograph and reduce thus the required spillway capacities. The potential to reduce the required additional spillway capacities at Fierza and Komani through implementation of sediment management was analyzed with the software REServoir CONservation 2 (RESCON 2) which has been developed recently by Fichtner. The studied sediment management options included deposit removal techniques, namely flushing and dredging, sediment routing techniques, i.e. sluicing, by-pass and density current venting and sediment inflow reduction techniques through implementation of catchment management.

The objective of the paper is to present the results of the performed RESCON 2 techno-economic analysis regarding the sediment management method that can reduce the currently observed storage loss rate without deteriorating the economic performance of the cascade. This way, the adequacy of the discharge capacity of the presently planned new spillways in Fierza and Komani can be extended to a longer time period. First the technical feasibility of the state of the art sediment management techniques is assessed. Subsequently the time path of storage development and the economic performance of the Fierza and Komani reservoir is calculated for the technically feasible sediment management techniques. The benefit assessment considers the impact of active storage conservation on the future water yield supply. The cost assessment includes the capital expenditures for implementation of sediment management, the corresponding annual operation and maintenance costs and the energy generation losses driven by the water consumed for sediment management.

1. Description of Drin River Cascade

Drin River Cascade is located in northern Albania on Drin River and comprises three storage hydropower schemes, namely Fierza, Komani and Vau I Dejes, moving from upstream to downstream. Vau i Dejes HPP (5 x 50 MW) was the first constructed during the years 1967 to 1971, followed by Fierza HPP (4 x 125 MW) constructed in the period 1971 to 1978. Komani HPP (4 x 150 MW) was the last addition in the period 1980- 1985. The key parameters of the corresponding storage reservoirs are provided in the table below.

Table 1. Key geometrical parameters of Drin River Cascade storage reservoirs

Parameter		Fierza	Komanni	Vau I Dejes
Pre-impoundment storage capacity [Mil. m³]	Active	2300	525	80
	Inactive	400	185	500
Existing storage capacity (Bathymetrical survey 2015) [Mil. m³]	Active	1900	445	75
	Inactive	300	165	380
Maximum pool elevation of reservoir [masl]		296.0	175.5	74
Minimum operation water level [masl]		240.0	161	70
Minimum reservoir bed elevation at dam site [masl]		170.0	75.5	30
Reservoir length [km]		70	38	26

The sediment loads in the reservoirs have been calibrated on basis of the measured deposits in the reservoirs and the calculated trap efficiency. The sediment transport of Drin River was strongly affected by the inundation of the three reservoirs that reduced essentially the flow velocities. The calculation has taken into account the sequence of reservoir impoundment and is presented in the following figure.

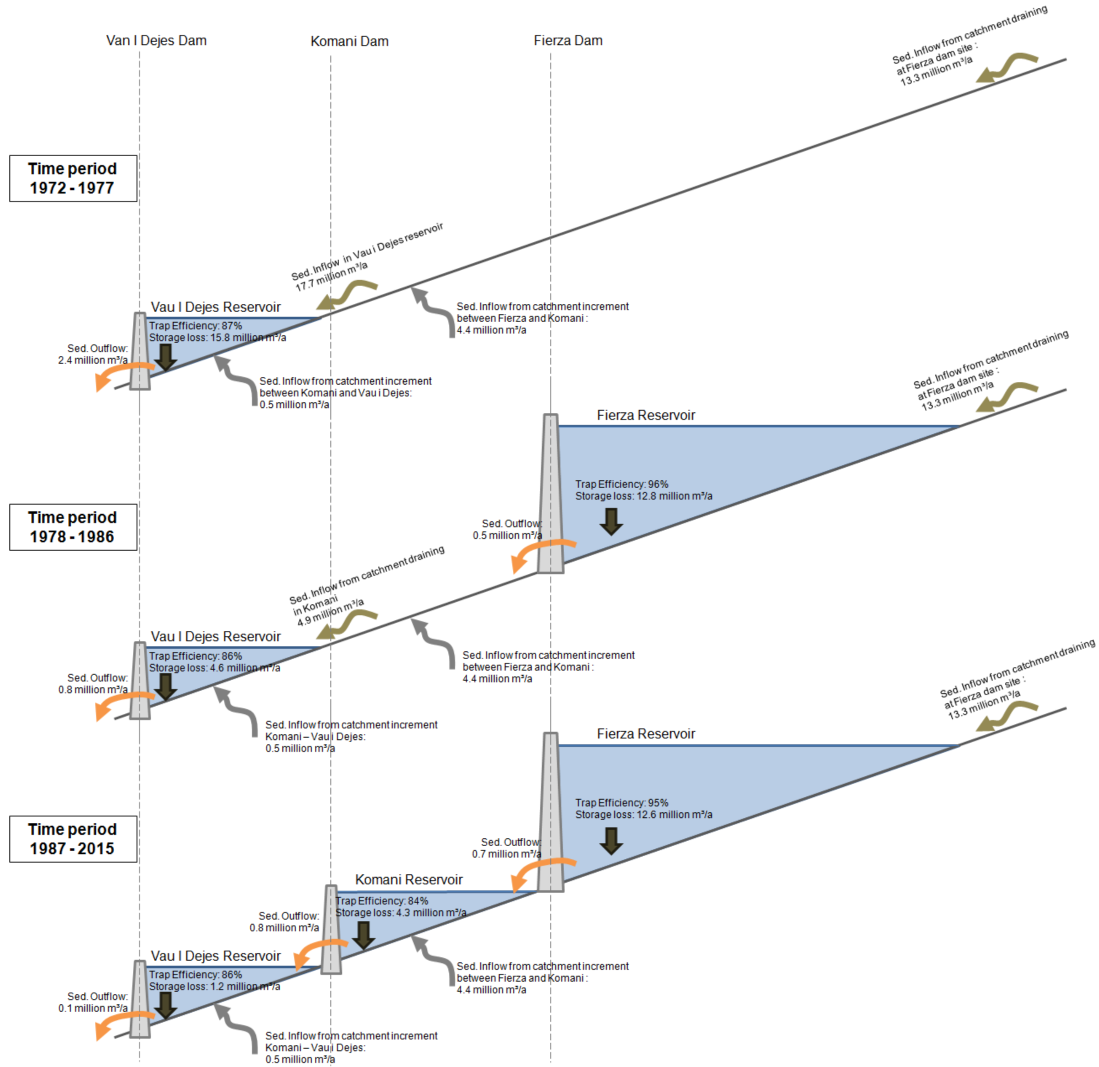


Fig. 1. Temporal and spatial evolution of sediment loads along the impounded reach of Drin River.

The above presented total sediment loads consider a partitioning between suspended and bedload 80% - 20%.

In year 2015 was performed the latest bathymetrical survey of the Drin River Cascade reservoirs. The comparison with the pre-impoundment topography revealed the amount and spatial pattern of sedimentation. The calculated sediment yields correlate very well with the actual sediment deposits. Furthermore the corresponding specific sediment yields are in good agreement with the corresponding values reported in the literature as well as with the results of empirical equations.

The Mean Annual Flow in Fierza, Komani and Vau i Dejes reservoir is 6455 million m³/a, 8960 million m³/a and 9460 million m³/a respectively. The hydrological and hydraulic modelling of the river basin and the reservoirs indicated that the existing spillways of Fierza and Komani lack capacity for safely discharging the PMF, and that the situation will deteriorate in the future due to progressive sedimentation of the reservoirs' active storage. The existing discharge capacity of Vau i Dejes spillway on the other hand is sufficient to evacuate the PMF flood event.

On these grounds, the contribution of sediment management in reservoir storage preservation and consequently on reduction of costs for additional spillway capacity for Fierza and Komani reservoir was investigated with application of the software RESCON 2 which serves for a rapid assessment of reservoir sustainability and the identification of technically feasible and economically optimal sediment management techniques.

2. RESErvoir CONServation 2 (RESCON 2) software

The RESCON approach was developed and published in 2003 by the World Bank (Palmieri et al. 2003) with the purpose to provide a tool that will allow the identification of the technically viable and economically optimal approach for sustainable management of water storage reservoirs. The experiences gained from the extensive use of the model the years after its publication as well the evolution of the state of the art in sediment management and economic theory, prompted the World Bank to proceed in an update and upgrade of the RESCON methodological approach and the accompanying software. The upgraded model RESCON 2 was recently developed by Fichtner for the World Bank Group will and be released in fall 2017. The improvements incorporated in RESCON 2 can be categorized as follows (Efthymiou et al. 2017):

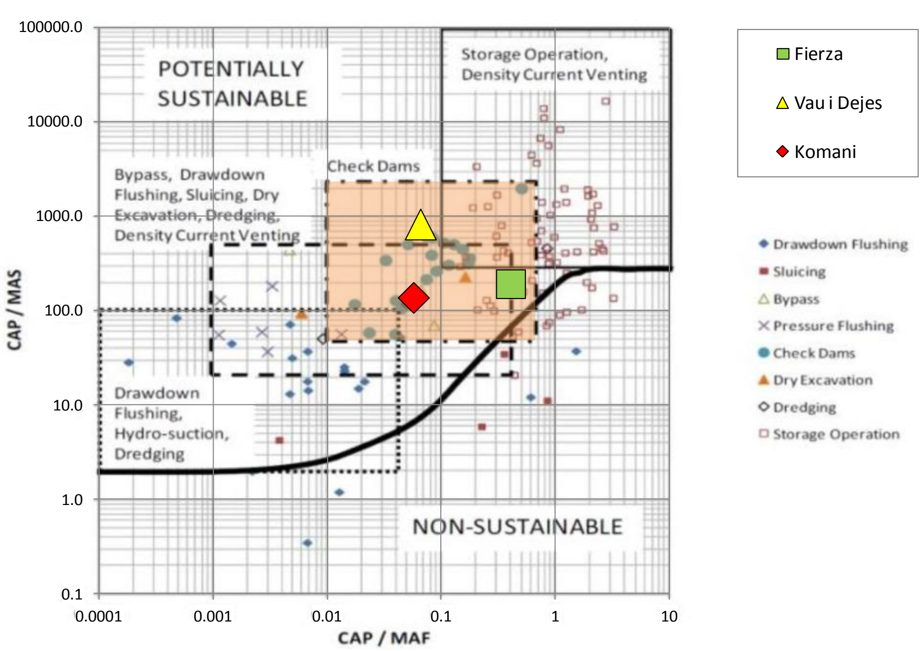
- Improvement of the applied procedure for calculation of the reservoir storage development
- Extension of palette of assessed sediment management techniques
- Better incorporation of intergenerational equity issues in performed economic appraisal
- Addition of a climate change analysis with purpose the assessment of sediment management as adaptation strategy for increasing the resilience of the infrastructure
- Enhancement of the user-friendliness during model setup and result reading through development of a Graphical User Interface (GUI)

It is pointed out that RESCON 2 is not intended to replace detailed studies. The RESCON 2 program is based on empirical methods and therefore sound engineering judgment is required for interpretation of the results. Furthermore in more advanced project development stages, the analysis shall be substantiated by detailed techno-economic studies and numerical or physical modelling.

3. Evaluation of sediment management options

Several sediment management approaches have been developed for counter fighting sedimentation and consequently the exhaustion of the natural resource of reservoir storage. Detailed descriptions of the available methods and techniques are included in Annnandale et al. (2016) and Morris and Fan (1998).

A first preliminary assessment of the most appropriate sediment management method was performed basised on the graph included in Annandale (2013) which allows for a first site specific identification of the most prominent sediment management techniques depending on the relative hydrologic and sedimentologic size of the reservoir. This preliminary assessment, which is presented in the figure below, indicated that catchment management is the most appropriate method for all three reservoirs. Fierza reservoir is large enough in order to consider the long term storage of sediment as most appropriate approach to handle incoming sediment.



Relative hydrologic size (CAP[1] / MAF[2])

Fierza: 0.41

Komani: 0.06

Vau I Dejes: 0.07

Relative sedimentologic size (CAP / MAS[3])

Fierza: 193

Komani: 138

Vau I Dejes: 827

[1] CAP: Available gross storage capacity in year 2015

[2] MAF: Mean Annual Water Flow in m³/a

[3] MAS: Mean Annual Sediment inflow in m³/a

Fig. 2. Preliminary assessment of sediment management techniques for Fierza Komani and Vau i Dejes reservoirs.

A more detailed investigation of the available sediment management techniques indicated that the only feasible options are catchment management, flushing and sluicing. The summary of the feasibility assessment is presented in the table below.

Table 3. Evaluation of technical feasibility of available sediment management techniques

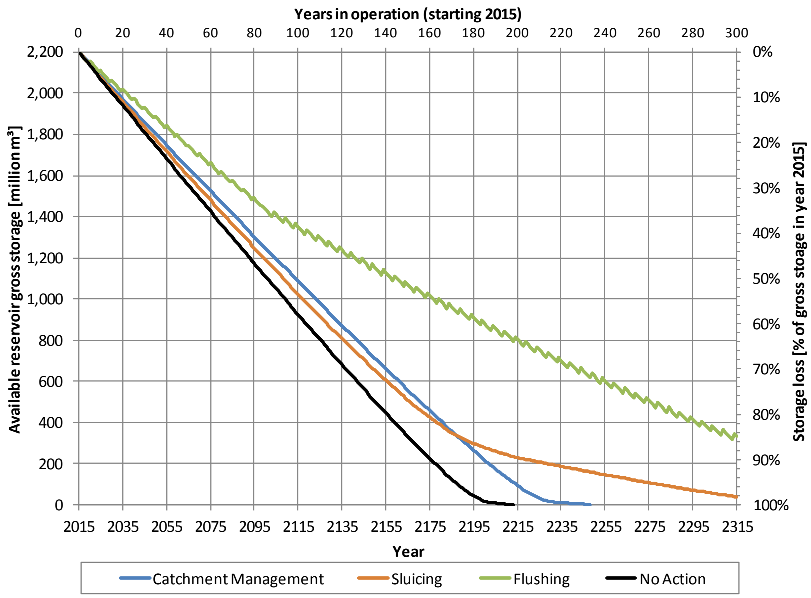
Method	Sed. Mgmt Technique	Feasibility	Reasoning
Catchment management	check dams	Feasible	Large number of tributaries with torrential character enter into the reservoirs
	Improvement of agricultural practices	Not feasible	The catchment area is already mostly forested
	Reforestation	Not feasible	
Deposit removal	Flushing	Feasible	According to Atkinson (1996) as implemented in RESCON 2
	Dredging	Not feasible	Very high economic cost due to large amounts of deposits that should be removed annually, lack of available disposal site in the proximity of the reservoirs
	Trucking	Not feasible	The reservoirs can't be completely emptied due to lack of outlet at the dam base. Same disposability problems as dredging
	Hydrosuction removal system	Not feasible	According to Hotchkiss (1995) as implemented in RESCON 2 Very low removal capacity limited only in the close vicinity of the dams. Disposal possible only at the downstream reservoir hence transposition of the problem to the next reservoir.
Sediment routing	Sediment by-pass		Construction of a by-pass tunnel or open channel practically not feasible because of reservoir length.
	Sluicing	Feasible	
	Density current venting	Not feasible	According to Morris and Fan (xxxx) as implemented in RESCON 2 the geometry of the reservoirs and the sediment concentrations do not favour the creation of density currents

The projection of the development of the gross storage of Fierza and Komani reservoir after implementation of the technically feasible sediment management techniques is presented in the following two figures. As reference, the figures contain also the time path of reservoir storage for the no action scenario. The specifications of the sediment management activities are presented on the right hand side of the storage time path plots.

The water level during flushing was selected in a first approximation equal with the sill elevation of the existing bottom outlets, since pressure flushing with limited water level drawdown would remove deposits only from the close vicinity of the outlet structure. The flushing discharge corresponds to the discharge capacity of the Fierza bottom outlet. It was considered that the flushing duration and discharge of Komani reservoir would be the same as at Fierza reservoir since flushing will be performed simultaneously in both reservoirs. An optimization analysis in both reservoirs indicated that the frequency of flushing events should be about five years.

The water level during sluicing corresponds to the minimum operating water level in order to minimize the energy generation losses. It has been considered that sluicing would be performed on annual basis with a duration of three months every year, including the time period of water level drawdown and refilling of the reservoir.

The reduction of bedload and suspended load due to construction of check dams in the catchment area of the reservoir was selected empirically based on values published in the technical relationship and engineering judgement. It was considered that check dams will have only a limited impact on the suspended yield entering the reservoirs, while the impact on bedload will be higher. The implementation of check dams is expected to be more effective in the case of Komani reservoir because of the geomorphologic characteristics of the catchment area draining in this reservoir. The assessment should be confirmed by detailed investigations that would reveal the locations highly susceptible to surface erosion in order to allocate and dimension the necessary check dam structures.

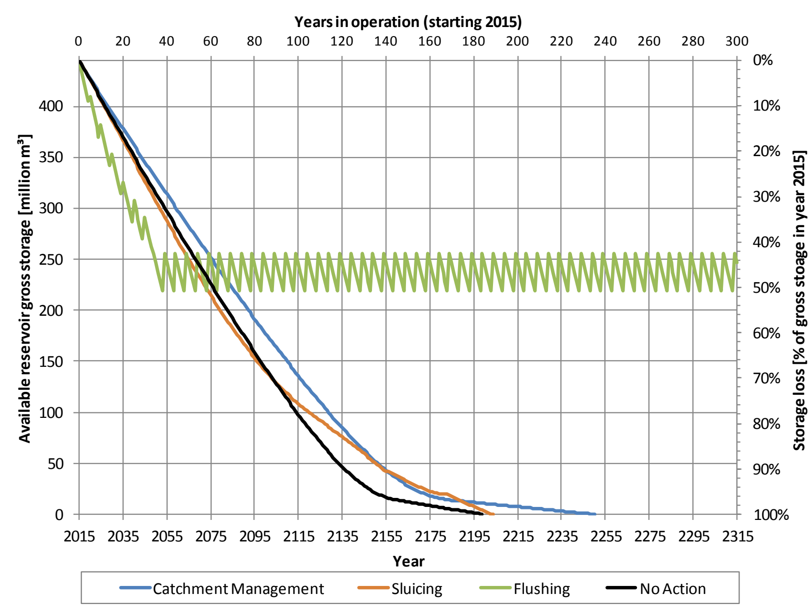


Catchment management	
Reduction of bedload:	30 %
Reduction of suspended load:	10%
Implementation year:	2017
Time lag until realization of its impact on sediment entry:	1 year
Sluicing	
Water level during sluicing:	275 masl
Duration of sluicing:	3 months
Implementation year:	2017
Flushing	
Frequency of flushing:	1 event / 5 years
Flushing discharge:	900 m³/s
Water level during flushing:	230 masl
Duration of flushing (including drawdown & refill):	4 months

Fig. 3. Fierza reservoir gross storage time path for the no action, flushing, sluicing and catchment management scenarios.

The analysis indicated that if no sediment management action is undertaken, the storage of Fierza reservoir will last approximately 180 years. Flushing is the most effective method to handle sedimentation and prolong the reservoir lifetime. It is also however the method associated with the highest water and energy losses. Sluicing and catchment management have a comparable impact on the development of available storage over time, with catchment management being slightly more effective at the beginning. The flushing analysis for Fierza indicated that the maximum amount of deposits that can be removed during each flushing event every five years is approximately 35 million m³/a. When sluicing is implemented on annual basis, the maximum amount of incoming sediment that can be routed through the reservoir is approximately 5 million m³ contrary to 0.7 million m³ that are routed currently.

The same analysis was performed also for Komani reservoir. The graphical plot of the Komani gross storage time path for the sediment management scenarios of flushing, sluicing and catchment management is shown in the following figure.



Catchment management	
Reduction of bedload:	40 %
Reduction of suspended load:	10%
Implementation year:	2017
Time lag until realization of its impact on sediment entry:	1 year
Sluicing	
Water level during sluicing:	161 masl
Duration of sluicing:	3 months
Implementation year:	2017
Flushing	
Frequency of flushing:	1 event / 5 years
Flushing discharge:	900 m³/s
Water level during flushing:	135 masl
Duration of flushing (including drawdown & refill):	4 months

Fig. 4. Komani reservoir gross storage time path for the no action, flushing, sluicing and catchment management scenarios.

RESCON 2 has been developed for application in standalone reservoirs and not for reservoirs belonging in a cascade. Therefore the assessment of flushing and sluicing in Komani required several modifications in order to account for the impact of the sediment management activities in the upstream reservoir of Fierza. For the flushing analysis, the sediment inflow in Komani had to be increased by the amount of deposits that are removed by flushing in the Fierza reservoir. Similarly, for the sluicing analysis the sediment inflow in Komani had to be increased in order to account for the sediment routed through Fierza reservoir during sluicing in this reservoir.

The analysis indicates that if no sediment management is applied in Komani reservoir, the lifetime of this reservoir will be approximately 180 years similar to Fierza reservoir. The following 70 years of operation, catchment management is the most effective method with regards to storage preservation. On the long term however, flushing appears to be more efficient with regards to storage preservation.

A faster storage loss is observed for the case of flushing the first 40 years of its operation. In this case, the deposits that are removed by means of flushing in Fierza will be conveyed to Komani and the flushing deposit removal capacity there, initially will not be enough to maintain the current storage loss rate at least. Therefore the reservoir storage loss will be faster than the currently observed for the following 40 years of operation. Subsequently the deposit removal capacity by means of flushing will balance the increased sediment inflows and the reservoir storage will be maintained in a sustainable manner. It appears that flushing in Komani is more effective than flushing in Fierza. The reason is that flushing in the downstream reservoir Komani shall be performed with the same flushing discharge as in the upstream reservoir Fierza due to the alignment of the two reservoirs in series. Fierza however is a much larger reservoir than Komani. Therefore flushing with the same discharge is relatively, i.e. the ratio of removed deposits to available storage, more effective in Komani as it is in Fierza. This explains why flushing can sustain the reservoir storage on the long term in Komani, while the storage of Fierza will continue dropping.

If sluicing is performed in Fierza reservoir, the simultaneous operation of sluicing in Komani will result in maintenance of the currently existing storage time path. In other words if sluicing is implemented in Fierza, sluicing in Komani is also necessary in order to protect the available reservoir storage from a faster depletion due to increased sediment inflows. Both flushing and sluicing are substantially more water demanding techniques than catchment management.

RESCON 2 performs a preliminary assessment of the economic performance of the reservoir expressed as the aggregated net present value of the reservoir benefits. The revenues are calculated by multiplying the firm water yield as calculated by the Gould-Dincer method with a fixed unit water yield rate. The calculated water yield is reduced in order to account for the water losses caused by sediment management activities. The costs correspond to the regular annual operation and maintenance costs increased by any costs associated with implementation of sediment management. The difference between revenues and costs determines the annual benefits which are consequently discounted and aggregated in order to calculate the total net present value of benefits throughout its operational lifetime. Discounting can be performed either with a fixed discount rate or with a declining discount rate. The impact of the implementation of sediment management on the economic performance of the Fierza and Komani reservoirs relative to the no action base line is illustrated in the figure below.

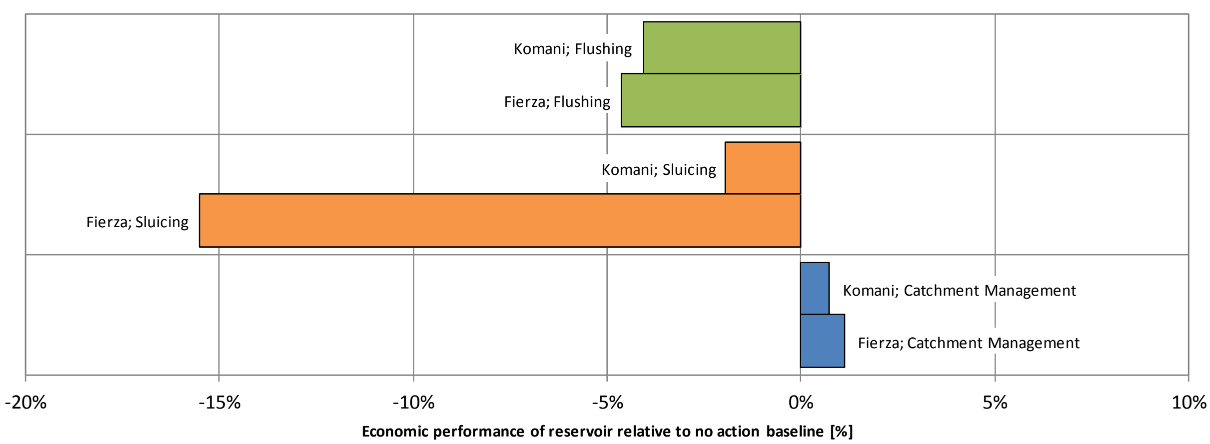


Fig. 5. Economic performance of Fierza and Komani reservoir relative to the no action scenario if catchment management, flushing and sluicing is implemented.

The implementation of catchment management with check dams in Fierza and Komani reservoirs will improve marginally the economic performance of both reservoirs. The reason is that the storage loss rate will be reduced and this will have a positive on the time path of the water yield that can be supplied by the reservoirs. The benefits from the increased water yield supply will exceed slightly the costs for construction and maintenance of the check dams and therefore will affect positively the overall economic performance of the reservoirs.

Flushing and sluicing will deteriorate the economic performance of the cascade since they will be associated with high water losses and reduction of the energy generation triggered by the necessary water level drawdown. The indirect cost introduced by the aforementioned water and energy losses will exceed essentially the positive impact of storage loss reduction. Therefore, it is expected that the overall economic performance of the both reservoirs will be negatively affected by these two sediment management activities. Furthermore it should be pointed out that the application of flushing and sluicing in Fierza and Komani would affect also the last reservoir of the cascade Vau i Dejes since they would cause a severe increase of the amount of sediment entering this reservoir. Therefore, sediment management would be required also in this reservoir.

4. Conclusions

The hydraulic and hydrologic modelling of the Drin River Cascade reservoirs indicated that the currently existing spillways in Fierza and Komani lack sufficient discharge capacity to safely evacuate the PMF flood event. Presently, additional spillways are being planned and shall be implemented in the future. The situation will deteriorate in the future due to progressing storage loss and the consequent reduction of the reservoir retention effect. The possibility to slow down the storage loss rate by means of sediment management has been investigated with application of RESCON 2, a software developed for the World Bank Group by Fichtner that serves for a rapid techno-economic assessment of the state-of-the-art sediment management techniques currently available.

The assessment of the technical feasibility and economic viability of all available state of the art sediment management techniques excluded dredging, trucking, hydrosuction removal, sediment by-pass and density current venting from any further considerations. The techniques of catchment management through implementation of check dams, full water level drawdown flushing and sluicing proved to be both technically feasible and economically viable and therefore were further analysed.

In Fierza reservoir flushing is the most effective method with regards to storage preservation while sluicing and catchment management have a comparable impact on the time path of storage development. The implementation of flushing and sluicing will increase substantially the sediment inflow in the downstream reservoir, Komani. This results in an accelerated storage loss rate for the following 40 years if flushing is implemented, while sluicing maintains the current situation with regards to storage loss rate but does not have at the same time a positive impact, since the water level drawdown to the minimum operating water level is not sufficient to route the increases sediment inflows out of the reservoir. Catchment management will reduce the currently observed storage loss rate.

The preliminary assessment of the economic performance of the reservoir indicates that flushing and sluicing will reduce essentially the total net present value of the benefits throughout the operational lifetime of both reservoirs because of the high water and energy losses due to water level drawdown. Catchment management with check dams will improve even marginally the economic performance because the benefits from reduction of the sedimentation will exceed the costs associated with implementation and maintenance of this method. Furthermore, catchment management will not have a negative impact on the last reservoir of the cascade, Vau i Dejes.

On these grounds it can be safely concluded that catchment management is the most appropriate method at least for the following 70-80 years for reducing the reservoir storage loss, maintaining the current economic performance and prolonging the adequacy of the presently planned spillways against PMF flood event.

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The Authors

Dr.-Ing. Nikolaos Efthymiou graduated in Civil Engineering from the Aristotle University of Thessaloniki in 2003. In 2004 he obtained a Master’s degree in Environmental Protection and Sustainable Development. From 2005 till 2012 he conducted research and worked in applied projects at the Institute of Hydraulic and Water Resources Engineering of Technical University of Munich on river engineering, addressing sediment transport of graded material in gravel-bed rivers. In 2012 he joined Fichtner GmbH & Co. KG where he is involved in due diligences, prefeasibility and feasibility studies for small and large hydropower projects as well as sedimentation studies. His expertise covers hydraulics and sediment transport. Nikos has worked on several reservoir sedimentation management projects worldwide and was responsible for development of the RESCON2 approach and software.

Dr.-Ing. Patrick Schäfer is a Civil Engineer and Project Manager in the Hydropower Department of Fichtner Consulting Engineers, Germany. He completed his Diploma in Civil Engineering at the Technische Universität München in 2000 and obtained the degree of Dr.-Ing. at the Institute of Hydraulic and Water Resources Engineering of the same University in 2006. In 2006 he joined Fichtner Consulting Engineers and since then contributed to a number of small and large hydropower projects, mainly in the stage of Feasibility Studies in Europe, Latin America, Africa, Southeast and Central Asia. He is specialized in hydraulic engineering, hydraulic structures and hydropower development. At Fichtner he is the Director for the Hydropower Studies Department.

Dr.- Ing. Hubert Hildebrand graduated in 1984 from the Faculty of Civil Engineering of the University of Karlsruhe, Germany. He completed his doctorate in 1993 in hydropower engineering with the doctoral thesis "Optimisation of Decentralised Hydropower Systems". From 1984 to 1991 he has been working as scientific researcher and lecturer at the Universities of Karlsruhe, Germany and Kyoto, Japan and joined the consulting firm of Fichtner, Germany in 1991. At Fichtner he holds the positions of the Chief Hydropower Engineer and Senior Manager Project Studies and Implementation.

Dr.-Ing. Sebastian Palt graduated in Civil engineering at the University of Karlsruhe in 1996. From 1996 to 2001 he completed his PhD thesis addressing sediment transport and its impact on hydropower development in mountainous regions at the University of Karlsruhe and was awarded with the Senator Huber award in 2002. In the same year he joined Fichtner as project manager and worked for various projects in Europe, Asia, Africa and Latin America. Between 2007 and 2010 he worked for project development in the International Development Department of E.ON Wasserkraft, where he was active mainly in the Balkan area, Turkey, Romania and France. Since 2013 he is the Executive Director of the Hydropower Department of Fichtner, Germany. He has worldwide experience in hydropower and development of reservoir sedimentation management approaches to ensure sustainable development. He was the principal in charge for development of the RESCON2 approach and software.

Mr. Fatos Bundo MSc graduated in 1988 in Civil Engineering at the Polytechnic University of Tirana and obtained his Master Degree on Industial and Civil constructions. In 2013 he obtained the diploma on Environment Impact Assessment from the University of Environment and Agriculture in Tirana. He has worked in both the private construction sector as well as governmental authorities. As director of the project implementation unit of the Ministry of Justice, he has been responsible for the projects financed by European Union for the judiciary in Albania As director of EU integration and EU projects in the Ministry of Environment, Forestry and Water Administration he has been the coordinator of all projects in environment sector in Albania. Since 2014 and up to date he is adviser of the Albanian Power Corporate (APC) which is responsible for the overall energy supply in Albania. He is the APC project manager of the project: Pre- and feasibility studies, preparation of tender design and technical specifications for providing safe flood management of the Drin Cascade Hydropower Plants, financed by the World Bank.