Multiple criteria design analysis of a compensation basin to mitigate hydro peaking

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Introduction

Hydropeaking is a major issue for storage hydropower plants. Hydropeaking can affect negatively the aquatic environment along river streams. For several hydropower plants studies which analyse measures to reduce the surge effect are currently under preparation. A common technical measure is to construct a compensation basin downstream of the powerhouse.

The selection of an adequate compensation basin volume is a compromise taking several aspects, such as construction costs, environmental impacts of the compensation basin during construction and operation as well as reduction of hydro peaking, into account. The determination of the required storage volume is based on different environmental factors. The main factors are surge ratio, discharge gradient, released maximum discharge and released minimum discharge.

However, the selection of these factors is complex and normally not a straightforward process. As for each river these factors can have a different environmental affect several cases have to be analysed. In addition the operational parameters of a hydropower plant, such as peaking hours and peaking discharge, can be varied.

This can lead to numerous simulation runs. The simulation – including checking and quality control – of hundreds of cases and a sensitive analysis is time consuming.

Design of experiments (DOE) provides a set of methods, which allows an identification of the factors with a significant influence on the storage volume. In addition by deriving a simple model, such as linear model, first estimations can be prepared. DOE is a promising set of methods which could reduce the significantly the required work regarding simulation runs.

1. Background

Hydropeaking is currently a major issue for operation of a hydropower plant. The sudden opening and closing of turbines can lead to highly unsteady flow conditions downstream of a tailrace, which is named as hydropeaking. This unnatural flow conditions can lead to a degradation of the ecosystem in and along a river stretch. Several Alpine rivers are affected by this issue, as shown by Minor and Möller (2007). A detailed analysis requires a comprehensive study, which takes technical, economic and environmental aspects into account. An example of such a comprehensive study is shown by Bieri (2012).

The measures to reduce hydropeaking can be classified in operational or constructional methods (VAW and LCH 2006). According to Wickenhäuser et. al (2004), the costs of operational measures are in average 3.5 times higher than constructional measures. The most common constructional measure is the creation of a compensation basin.

The basic function of the compensation basin is to retain turbine water during peaking hours and to release it during hours with little discharge.

The selection of an appropriate volume of the compensation basin is a challenging issue. Beside a location specific technical design also environmental criteria have to be taken into account. The quantitative parameters applied for the description of the hydropeaking are described in VAW and LCH (2006) and summarized in Table 1 with a definition of the parameters in Figure 1.

Input	Parameters	Indicators for surge
inflow time series Q(t,x)	daily max. discharge Q_{max}	surge ratio Q_{max}/Q_{min}
	daily min. discharge Q_{min}	difference pos.surge and neg. surge $deltaQ= Q_{max} - Q_{min}$
	daily mean discharge Q_{mean}	relative difference pos.surge and neg. surge $deltaQ/Q_{mean}$
	gradient discharge dQ/dt	gradient discharge and frequency
water level time series WL (t,x)	daily max. water level WL_{max}	difference water level $deltaWL = WL_{max} - WL_{min}$
	daily min. water level WL_{min}	
	gradient water level dWL/dt	

Table 1: Surge Parameters (based on VAW and LCH 2006)

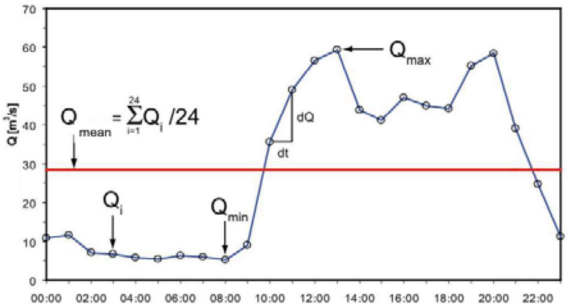

Figure 1: Surge Parameters (VAW and LCH 2006)

Based on environmental studies for all or some of these parameters, target values can be defined. These target values are typically defined as a range, especially in an early stage of planning. In the present study following environmental target parameters have been selected (see Figure 2):

- minimum regulated flow (Q_{rmin})
- discharge gradient (DG=dQ/dt)
- maximum regulated flow (Q_{rmax})
- surge ratio ($SR=Q_{rmax}/Q_{rmin}$)

In addition, variables which defines the operation of the power plant (peaking time (t_p) and peaking discharge (Q_{peak}) have to be defined. As we focus on the daily surge effect with small fluctuations of the natural flow in the river (Q_{nat}) a constant value can be assumed for each simulated day.

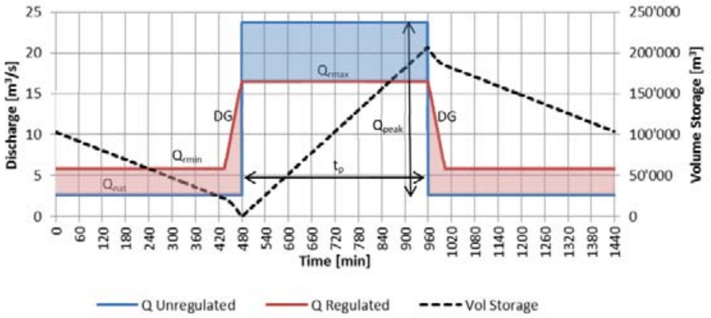

Figure 2: Schematic Figure of Factors

2. Simulation Model

A simulation model has been elaborated. It is based on the storage equation (eq. 1)

$$Q_{in} \quad Q_{out} \quad \Delta S \qquad (1)$$

where Q_{in} is the average inflow in time, Q_{out} is the average outflow and ΔS is the change in storage. A simulation constrain is that the stored water volume over one day (red area on Figure 2) must be equal to the released water (blue area on Figure 2).

The model requires the following input factors:

- minimum regulated flow (Q_{rmin})
- natural flow (Q_{nat})
- discharge gradient (DG)
- peaking time (t_p)
- peaking discharge (Q_{peak})

For the analysed case, the upper and lower limit of each factor is shown in Table 2.

The simulation model allows the calculation of the following responses:

- maximum regulated flow (Q_{rmax})
- surge ratio (SR)
- active storage (AS)

In the following sections we focus on the active storage as main response.

		Lower setting	Upper setting
minimum regulated flow	[m^3/s]	5.8	7.7
natural flow	[m^3/s]	2.24	2.688
discharge gradient	[$m^3/s/min$]	0.08	0.242
peaking time	[h/day]	8	12
peaking discharge	[m^3/s]	21	24.5

Table 2: Upper and Lower Limit of Factors

3. Design of Experiments

In early stage of planning only limited time is available. DOE provides a set of methods, which allows a reduction of the simulation runs, by still allowing a screening of the key factors as well as an elaboration of a simplified equation for an estimation of the active storage. This model can be used also for cross-checking simulation results in a later planning stage.

Different experimental designs for the surge analysis were selected and compared.

- Fractional factorial design, resolution III ($2_{III}^{5\ 2}$)

- Fractional factorial design, resolution V (2_V^{5-1})
- Full factorial design (2^5)

For the fractional factorial as well as for the full factorial design linear models were established (eq. 2). In order to check if a linear model is appropriate, the residuals were analysed.

$$y = a_0 + \sum_{i=1}^{5} a_i x_i + \sum_{i,j=i+1}^{5} a_{ij} x_i x_j + e_i \qquad (2)$$

Finally the three different experimental design approaches are compared taking into account the following criteria:

- allowing a reliable estimation of the active storage volume,
- possibility to identify the key factors affecting the active storage,
- reduction of simulation runs.

4. Models and Results

Fractional Factorial Design 2_{III}^{5-2}

In a first step the fractional factorial design with a resolution of III was selected. This design method is generally applied for a first screening of main effects. It allows a reduction of the simulation runs to 8. The generator used for the computation of the fourth column is ±4=12 and for the fifth column ±5=13 (Box, 1978). With this generator the design has the minimum aberration. The matrix of experiments is shown in Table 3.

Run	**X_1**	**X_2**	**X_3**	**X_4**	**X_5**
1	-1	-1	-1	1	1
2	1	-1	-1	-1	-1
3	-1	1	-1	-1	1
4	1	1	-1	1	-1
5	-1	-1	1	1	-1
6	1	-1	1	-1	1
7	-1	1	1	-1	-1
8	1	1	1	1	1

Table 3: Matrix of Experiments for the Fractional Factorial Design - Resolution III

With this approach the focus is only on the main effects (a_i) and we assume that the interaction effects are small. Main effects are confounded with two factors interactions (a_{ij}). The aliases for the main effects and two factors interactions only are listed below.

$$\{a_1; a_{24}; a_{35}\}, \{a_2; a_{14}\}, \{a_3; a_{15}\}, \{a_4; a_{12}\}, \{a_5; a_{13}\}, \{a_{23}; a_{45}\}, \{a_{25}; a_{34}\}$$

In a following step, based on the matrix of experiments, the response vector Y was obtained in the simulation model. The model matrix X (see Table 4) was then prepared taking into account a linear model:

$$Y = X\alpha + \varepsilon \qquad (3)$$

where Y is the response matrix, X the model matrix, α the model coefficients vector and ε the residual errors vector. As the model matrix is orthogonal, the model coefficients can be calculated with the following formula:

$$\alpha = \frac{1}{N} \cdot X^T \cdot Y \qquad (4)$$

where N is the number of experiments.

Run	I	a_1 $=a_{24}$ $=a_{35}$	a_2 $=a_{14}$	a_3 $=a_{15}$	a_4 $=a_{12}$	a_5 $=a_{13}$
1	1	-1	-1	-1	1	1
2	1	1	-1	-1	-1	-1
3	1	-1	1	-1	-1	1
4	1	1	1	-1	1	-1
5	1	-1	-1	1	1	-1
6	1	1	-1	1	-1	1
7	1	-1	1	1	-1	-1
8	1	1	1	1	1	1

Table 4: Model Matrix for the Fractional Factorial Design - Resolution III

Figure 3 shows the relative effect on the active storage of each calculated factor. The minimum regulated flow (coefficient a_1) and the discharge gradient (coefficient a_3) have the strongest effect. The analysis suggests that all coefficients have a significant effect and none of these should be neglected so far. It is not surprising as it was known that all five factors have an effect on the storage volume. The coefficient a_1 has the biggest effect. But it is aliased to two interactions, and should thus be investigated further.

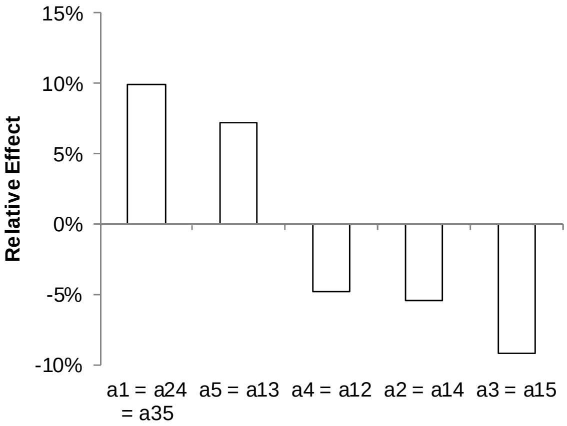

Figure 3: Relative Effects for the Fractional Factorial Design - Resolution III

Figure 4 shows the plot of residuals. The figure suggests that a linear model is appropriate. However, it should be noted that the sample size is small and therefore it is only a weak indication.

The comparison of the simulation results and the active storage calculated with the linear model considering the five factors shows a good fitting (see Figure 5). The regression functions leads to active storages, which differ less than ±5% from the simulated values.

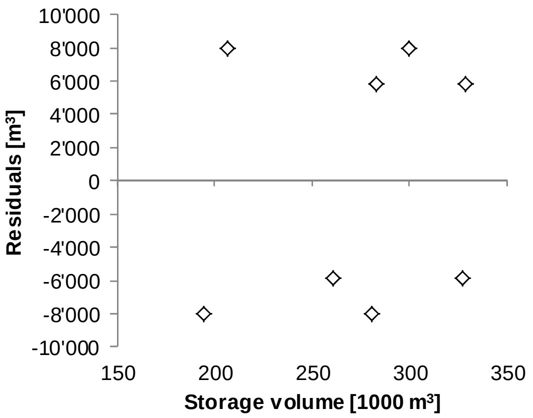

Figure 4: Plot of Residuals

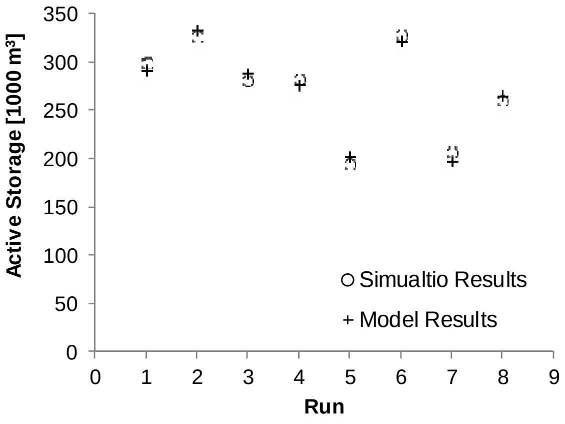

Figure 5: Comparison of Simulation and Model Results

Fractional Factorial Design 2^{5-1}_{V}

In a second step a fractional factorial design with resolution V was selected, in order to focus on finding the main effects and the 2-way interactions. Compared to the full fractional design the ability to estimate interaction effects is reduced. However, findings described in the previous section indicate that the interactions have a small effect. With a resolution of V the number of simulation runs can be reduced to 16.

The use of a complete fold over of the previous design was considered, but it only gives a resolution of IV. The aliases would be the following:

$$\{a_{23}: a_{45}\}, \{a_{24}: a_{35}\}, \{a_{25}: a_{34}\}$$

With this resolution V design chosen, no main effects are confounded with any 2-way or 3-way interactions. The main effects are only confounded with the 4-way interactions. With equation 2 the coefficients (a_i and a_{ij}) were calculated.

The experiment matrix is given in Table 5. The key factors are relative the minimum regulated flow (coefficient a_1) and the discharge gradient (coefficient a_3). The results support the findings based on the fractional factorial design with resolution III.

Run	X_1	X_2	X_3	X_4	X_5
1	-1	1	1	-1	1
2	1	1	1	-1	-1
3	-1	-1	1	-1	-1
4	1	-1	1	-1	1
5	-1	1	-1	-1	-1
6	1	1	-1	-1	1
7	-1	-1	-1	-1	1
8	1	-1	-1	-1	-1
9	-1	1	1	1	-1
10	1	1	1	1	1
11	-1	-1	1	1	1
12	1	-1	1	1	-1
13	-1	1	-1	1	1
14	1	1	-1	1	-1
15	-1	-1	-1	1	-1
16	1	-1	-1	1	1

Table 5: Matrix of Experiments for the Fractional Factorial Design - Resolution V

If all main factor and 2-way interactions are taken into account, the regression function allows an estimation of the active storage with a perfect accuracy. However, only the coefficients with relative effects higher than 4 % were kept leading to an accuracy of the storage volume of ±10%. These coefficients are a_1, a_3, a_4 and a_5 (all main coefficients except the natural flow).

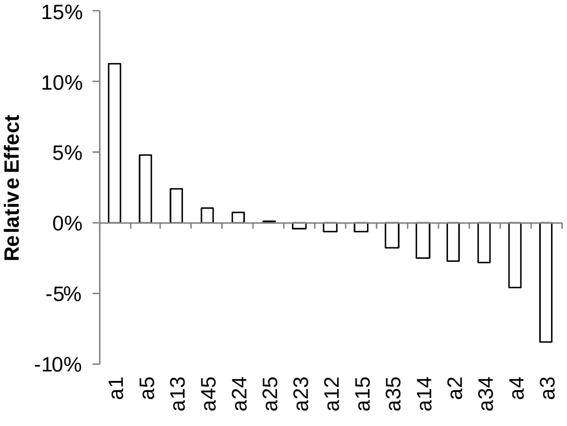

Figure 6: Relative Effects for the Fractional Factorial Design - Resolution V

In order to check if the selected model is appropriate the residuals are analysed. Figure 7 shows the residuals versus predicted values. The residuals are randomly distributed around zero, which indicates that the assumption that the relationship is linear is reasonable. Figure 8 shows the difference between the simulation and the model.

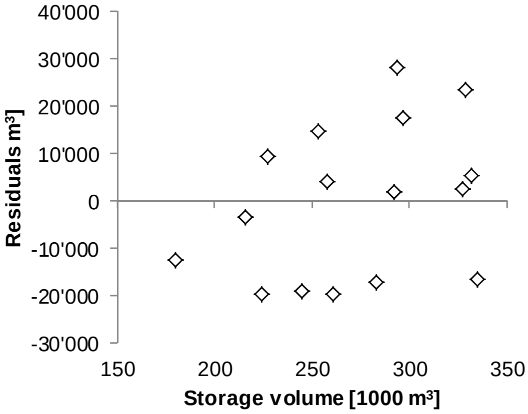

Figure 7: Plot of Residuals

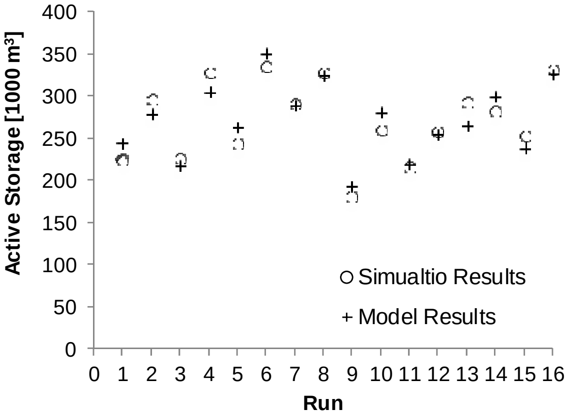

Figure 8: Comparison of Simulation and Model Results

Full Factorial Design 2^5

Finally a full factorial design was selected to see if precision can be added to the previous design. All five main effects and all ten 2-way interactions are estimated. 3-way, 4-way and 4-way interactions are neglected. 32 simulation runs are required.

The minimum regulated flow (see parameter a_l in Figure 9) has the largest effect, followed by the discharge gradient (a_3), the peaking discharge (a_5), the peaking time (a_4) and finally the natural flow (a_2). It confirms the findings of the fractional factorial designs.

The 2-way interactions are considerably small. The 2-way interactions a_{13} (interaction between minimum regulated flow and discharge gradient), a_{34} (discharge gradient and peaking discharge) and a_{14} (minimum regulated flow and peaking time) show the largest effect out of the 2-way interactions.

Within the 4 previous main factors used previously, the accuracy of the estimated active storage is ±12%. This is worst that before. It was thus chosen to reduce all coefficients with a value higher than 2 % (all main factors and the 3 interactions cited before) (see Figure 10). This model leads to an accuracy of ±5.5%.

Again with the full factorial design the residuals are randomly distributed around the zero (Figure 11). It supports the assumption of a linear model.

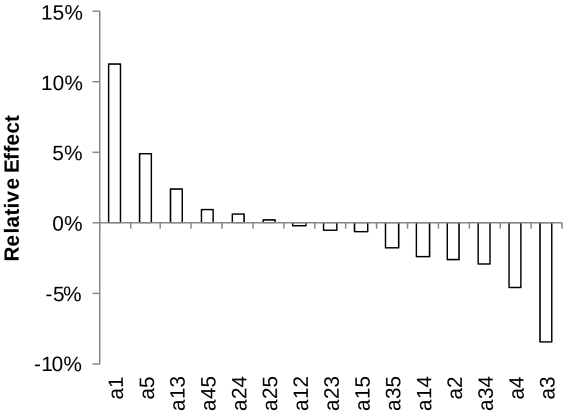

Figure 9: Relative Effects for the Full Factorial Design

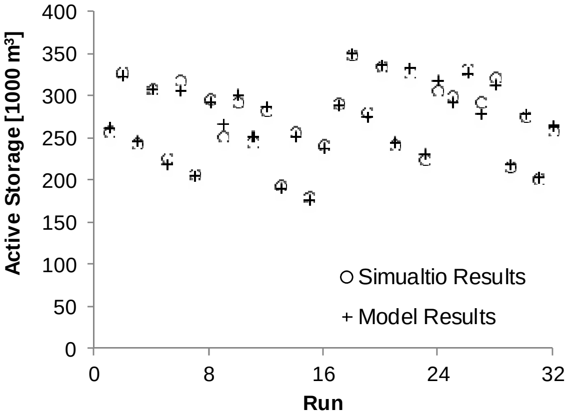

Figure 10: Comparison of Simulation and Model Results

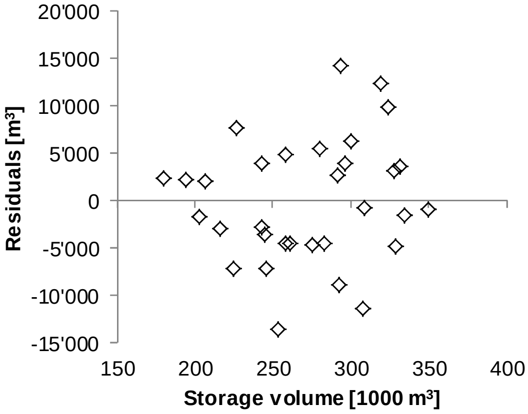

Figure 11: Plot of Residuals

Figure 12 shows the interaction of the coefficient a_{13} between the minimum regulated flow and the Discharge Gradient. The storage volume is higher for low value of the Discharge Gradient. This interaction is smaller for high values of the Minimum Regulated Flow.

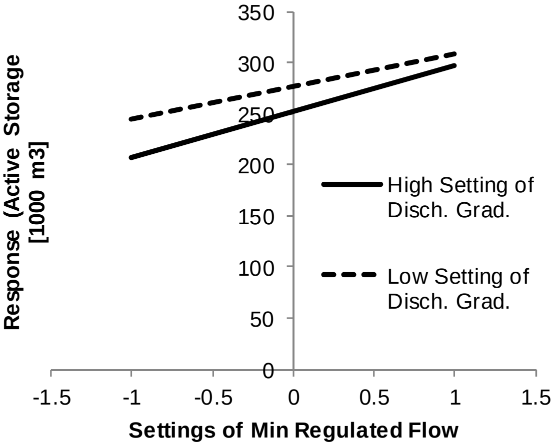

Figure 12: Interaction Discharge Gradient and Minimum Regulated Flow

Figure 13 shows the interaction of the coefficient a_{14} between the minimum regulated flow and the Peaking Time. The storage volume is almost the same for low values of the minimum regulated flow, but it is higher for higher values of the peaking time when the minimum regulated flow is high.

The third interaction a_{34} between the discharge gradient and the peaking time shows that the storage volume is higher for low settings of low peaking time (Figure 14).

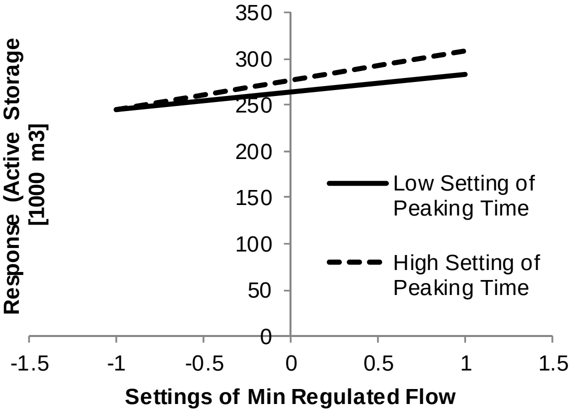

Figure 13: Interaction Peaking Time and Minimum Regulated Flow

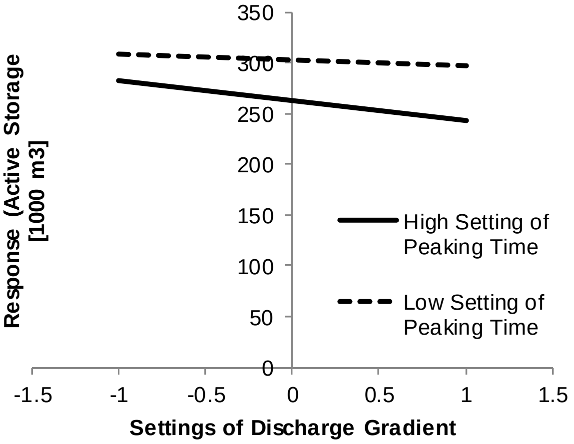

Figure 14: Interaction Peaking Time and Discharge Gradient

5. Comparison

The objective of this work is to find a design approach which fulfils best the following criteria:

- allowing a reliable estimation of the active storage volume,
- possibility to identify the key factors affecting the active storage,
- reduction of simulation runs

All three applied designs allow a reliable estimation of the active storage. The design with the lowest accuracy (2^{5-1}_{V}) leads to an accuracy of about ±10%. This can be acceptable in an early planning stage.
With all three methods the key factors can be identified. Compared to the two other design approaches, the fractional factorial design 2^{5-2}_{III} shows a higher influence of the natural flow (Q_{nat}) than the peaking time (t_p) (see Table 6). However, as the coefficients have almost the same relative effect this was found to be negligible.

Ranking	Fractional Factorial Design, Resolution III	Fractional Factorial Design, Resolution V	Full Factorial
1	Q_{rmin} (a_1)	Q_{rmin} (a_1)	Q_{rmin} (a_1)
2	DG (a_3)	DG (a_3)	DG (a_3)
3	Q_{peak} (a_5)	Q_{peak} (a_5)	Q_{peak} (a_5)
4	Q_{nat} (a_2)	t_p (a_4)	t_p (a_4)
5	t_p (a_4)	Q_{nat} (a_2)	Q_{nat} (a_2)

Table 6: Ranking of Factors

Figure 15 shows the effects of all three models. The main difference is the inclusion of the coefficient a_2 in the 2^{5-2}_{III} design. Coefficient a_5 is also significantly different. The full factorial design only slightly changes the values from the fractional design 2^{5-1}_{V}.

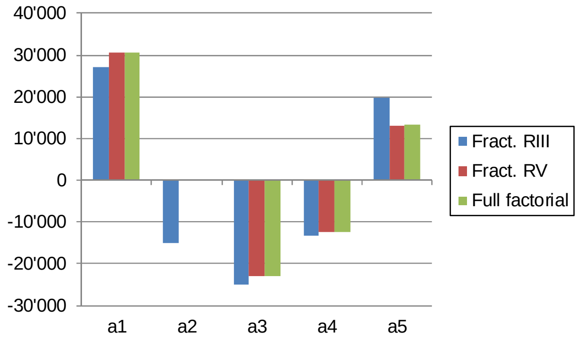

Figure 15 : Comparison of the Effects of Main Factors

6. Conclusions

A fractional factorial design 2^{5-2}_{III} combined with a linear model leads to very satisfying results. The simulation runs can be reduced significantly and the main effects can be identified. Using only the five factors without interactions, the accuracy on the storage volume is ±5 %. This is largely acceptable in an early stage of design.
If a fractional factorial design 2^{5-1}_{V} is applied and all effects (a_i and a_{ij}) are taken into account the residuals are equal to zero. Without any interactions the accuracy of ±10 % is lower than the 2^{5-2}_{III} design.
A full factorial design leads does not lead to a significant improvement.
In this case the minimum regulated outflow and the design discharge have the largest effect on the active storage. This information is important for the engineer designing a compensation basin.
This work shows that by applying DOE, the required simulation runs for an analysis of hydropeaking can be significantly reduced by still providing reliable estimations of the active storage. The 2^{5-2}_{III} design is very efficient to

find a linear model good enough to be used in a preliminary design of a compensation basin. The key factors can be identified and a simplified equation can be elaborated, which could be also applied for cross-checking simulation results in a later planning stage.

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