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Benchmarking small-scale pumped hydro schemes that have potential for flood management benefits

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Abstract

Flood risk is increasing due to climate change and small rural communities are increasingly impacted. Constrained governmental budgets lead to inadequate funding for smaller communities leaving them at ever-increasing risk. Integrating small scale pumped hydro into new fluvial flood attenuation provides an opportunity to generate revenue from the purchase and sale of electricity. This revenue may provide the necessary funding to enable a flood risk management scheme to progress. A review of literature found no existing methodology for combined assessment of flood risk and energy storage assets. Therefore, a bespoke methodology was developed to evaluate proposals at a community in Dawlish, Devon, UK. Key parameters from flood risk management and energy power generation were collated into a methodology for testing using river flow data from the study site. Key performance indicators were generated for a range of configurations. Initial results suggested an installation could provide modest positive economic returns whilst delivering desired flood risk benefits. Further work is recommended to refine the methodology, test sensitivity and establish the range of sites where this technique may be adopted.

Highlights

- A method for the evaluation of flood attenuation with integrated pumped hydro energy storage is developed and initial results explored
- A range of installation sizes were tested with modest return on investment established
- Further investigation into model sensitivity and breadth of application should be undertaken

Introduction

Effective flood risk management is integral to the protection of people and property in a changing climate. Economic losses in England and Wales attributed to flooding averaged £250m per annum between 1990 and 2014 (Thorne, 2014) with substantial losses of £1.3Bn experienced during the events of winter 2013/14 (EA, 2016). Delivery of flood risk schemes to allow communities to adapt to increased flood risk due to climate change is challenging within current funding rules. Flood risk schemes in England are traditionally funded from government ‘Grant in Aid’ and a small proportion of ‘partnership funding’ from other sources to cover remaining costs. Strict funding allocation rules mean small rural schemes are eligible for less government funding whilst also have limited opportunities for funding from other sources. As such, alternative models to deliver flood risk management are required. A synergy has been identified as the steep topographies which can be a threat for flooding in small (<25km^2) catchments also lend themselves to opportunities to generate electrical power from the flow of water.

Traditional medium-head (30 – 300m) hydropower generation has proven uneconomic in lowland UK (Rehman, Al-Hadhrami, & Alam, 2015), however the changing energy supply and demand patterns due to increased uptake in renewables establishes a need for greater energy storage (Gisseya, Doddsa, & Radcliffe, 2018). The UK electricity system will be core to the net zero transition as transport and heat are steadily electrified (Riverswan Energy Advisory, 2021). Integrating pumped hydro energy storage into flood risk management to store water and energy has never previously been explored in lowland UK terrain. Distribution scale long duration energy storage is a valuable asset required to support distributed renewables development (Gisseya, Doddsa, & Radcliffe, 2018) particularly present from the abundance of solar farms across the southwest peninsula of England. However, the case for deployment of low head, low power installations are generally ruled out on a perception of excessive capital cost resulting in poor economic performance. The opportunity to incorporate flood risk functionality and the associated capital funding has never previously been investigated. This paper develops a preliminary methodology to examine the economic viability of delivering flood risk management with small scale pumped hydro energy storage in lowland UK. The outcome of this research will be to evaluate the economic viability of a proposal that reduces flood risk in small urban settlements in lowland UK.

Methodology

A literature review of existing Pumped Hydro Energy Storage (PHES) and flood risk management design and assessment methodologies was completed which identified no existing solutions for combined evaluation. With a research gap identified, a methodology was developed to test a range of storage configurations and enable the calculation of key performance metrics. A mass balance simulation approach was adopted based on the design of flood storage reservoirs (FSR), with the following key parameters: flood attenuation volume (m^3); peak attenuation rate (m^3/s); and safe pass forward flow[1] (m^3/s). The full list of parameters adopted within this conceptualised methodology for the modelling of energy storage role along site flood storage functionality are illustrated in Figure 1.

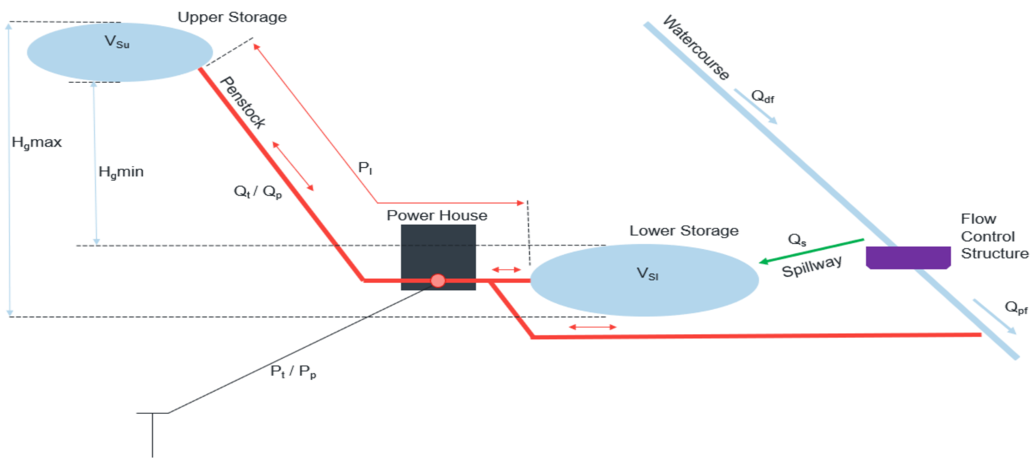

Figure 1 - Conceptual model of Pumped Hydro Flood Storage concept developed

V_{su} = Volume of upper storage (m^3), H_{gmax} = Maximum gross head difference (m), H_{gmin} = Minimum gross head difference (m), P_l = Penstock length (m), Q_t = Turbine flow rate(m^3/s), Q_p = Pumping flow rate(m^3/s), P_t = Electrical power during turbining (kW), P_p = Electrical power during pumping (kW), V_{sl} = Volume of lower storage (m^3), Q_{df} = Design flood flow (m^3/s), Q_s = Exceedance flow over spillway (m^3/s), Q_{pf} = Pass forward flow (m^3/s)

The assessment model development consisted of the following four steps:

[1] The peak flow that can be safely conveyed by the downstream infrastructure prior to flooding

One - Hydrological Evaluation:

A flood hydrograph, obtained from a flow gauging station at the study site (reference: 45171) is used to provide a design flood event for the purpose of modelling. This event aligned well with peak flows calculated for a 2% AEP flood event at the site. The use of the recorded flood hydrograph provides a more robust representation of total flood volume critical for the performance assessment of a flood attenuation solution. The conveyance capacity of the downstream channel was deducted from the recorded flood flows to calculate the flood attenuation rate required at 6-minute timesteps. The total flood attenuation volume and peak flow attenuation could then be calculated to allow infrastructure sizing.

Two - Infrastructure Design:

Peak river flow, flood event duration and total flood volume are used to inform the total volume of water to be stored between the upper and lower storage areas. This informs the combination of pump capacity and reservoir sizes that satisfy the total flood attenuation required. For energy operation modelling it was assumed that turbine capacity (m^3/s) is equal to pump capacity therefore flows and headlosses within the penstock are the same during both operations. The lower reservoir location is chosen based on industry guidance within the Fluvial Design guide (Ackers & Bartlett, 2009). The upper reservoir location was determined by the maximum gross head difference between lower and upper reservoirs calculated from LiDAR[2] derived digital terrain model. Maximising head difference is recognised best practice to achieve optimum economic return for pumped hydro installations and therefore was also adopted for this methodology (Rehman, Al-Hadhrami, & Alam, 2015).

Three - Estimation of Capital Expenditure:

Cost curves were developed for key infrastructure elements required for an installation from literature and following engagement with industry sources. Fixed percentages are adopted for ancillary costs such as preliminaries, fees, project management, design and consenting, obtained from literature and sources within project development.

The following key infrastructure elements were included:

- Upper storage
- Lower storage
- Penstock
- Pumphouse
- Mechanical and electrical components associated with pumps and turbines
- Watercourse flow control structure and spillway
- Electricity grid connection
- Capital ancillaries

Four – Economic Evaluation:

Forecast revenue (£) based on generator output (kW) and energy storage duration (hrs) were obtained from industry (Cornwall Insights, 2023) for a 30-year period of operation (2027 - 2057). For this initial research, a simple metric of return on investment (%) was adopted to compare system configuration. Installation configurations were limited by energy storage durations between four and twenty hours where assumptions on future energy revenues were considered suitable.

This methodology enables comparison of economic viability of a PHFS installation for a range of infrastructure configurations enabling a range of scenarios to be tested.

[2] Light Detection and Ranging (LiDAR)

Case study

The methodology was tested at Dawlish Water, a 20km^2 steeply draining catchment in southwest England extending from the Haldon Hills at nearly 300mAOD, flowing through the Ashcombe valley into Dawlish Town. Key site variables are provided in Table 1. The town of Dawlish has a long history of frequent flooding (four events in the last 10 years) and is typical of topographical and hydrological features of a small rural catchment in southwest England. A single river level gauge operated by the Environment Agency, provides a record since 2012. River level data was available at 6-minute timesteps and converted into flow using the Manning formula. The largest flood event on record from the 2012 – 2024 synthesised flow record occurred on the 26th November 2012 and was used to provide the hydrograph for initial model testing.

Table 1 - Catchment parameters

Variable	Value	Description
Catchment area (km^2)	20.0	Area of catchment upstream of Dawlish Town
Peak flood flow (m^3/s)	20.5	Peak flow experienced on 26th November 2012
Safe pass forward flow (m^3/s)	11.0	Channel capacity through Dawlish Town prior to the onset of property flooding
Gross head (m)	85	Gross elevation difference between proposed upper and lower reservoirs
Flood funding available (£k)	4556	Total amount of government funding available to manage flood risk at Dawlish Town
Power export limit (kW)	2000	Maximum power export capacity on the electricity distribution network at this site
Maximum upper storage (m^3)	30000	Topographical constraints mean the upper storage volume is limited at this site.

Results and Discussion

A total of 100,630m^3 flood storage was required to attenuate the 2012 flood event. A linear relationship was observed between pump rate and reservoir storage size. As pump rate increases the utilisation of the upper reservoir increases, decreasing the volume of the lower reservoir required to attenuate the design flood event.

Pump rates were limited to between 0.5m^3/s and 1.7m^3/s to maintain configurations with specified limits of energy storage durations for revenue calculations and are consistent with accepted definition of long duration energy storage (BEIS, 2021). Estimated installation costs for the modelled case study range from £6.29m to £10.51m following a trend of increasing costs as pump capacity increases. This suggests costs of mechanical and electrical equipment, and penstock costs increase at a greater rate than reductions in reservoir construction costs.

Pump capacity increases correspond with increased generation capacity and revenue income. Flood funding available at the site is £4.56m indicating a funding gap of between £1.74m – £5.95m (which would need to be funded from debt repaid by revenue from energy arbitrage at the site). Figure 2 shows return on investment peaked at 4.97% (0.7m^3/s pump rate) with a minimum value of 3.33% (1.7m^3/s pump rate) demonstrating modest returns on investment. Results (see Table 2) suggest unit costs (£/kW and £/kWh) both exceed values for storage durations adopting Li-ion BESS or large scale pumped hydro technology. This is reflected in the ROI (%) values observed.

Table 2 – PHFS performance results at the Dawlish study site.

Q_p	P_t	V_{sl}	Storage (hrs)	ROI (%)	£/kW	£/kWh
0.5	353	101334	16.7	4.47%	4929	295
0.6	423	99534	13.9	4.81%	4483	323
0.7	494	97734	11.9	4.97%	4245	357
0.8	565	95934	10.4	4.64%	4426	426
0.9	635	94183	9.3	4.73%	4245	456
1.0	706	92473	8.3	4.44%	4389	529
1.1	777	90846	7.6	3.95%	4824	635
1.2	848	89226	6.9	3.77%	4917	713
1.3	919	87606	6.4	3.75%	4828	754
1.4	990	85986	6	3.80%	4754	792
1.5	1061	84366	5.6	3.76%	4686	837
1.6	1130	82746	5.2	3.46%	4866	936
1.7	1202	81177	4.9	3.33%	4951	1010

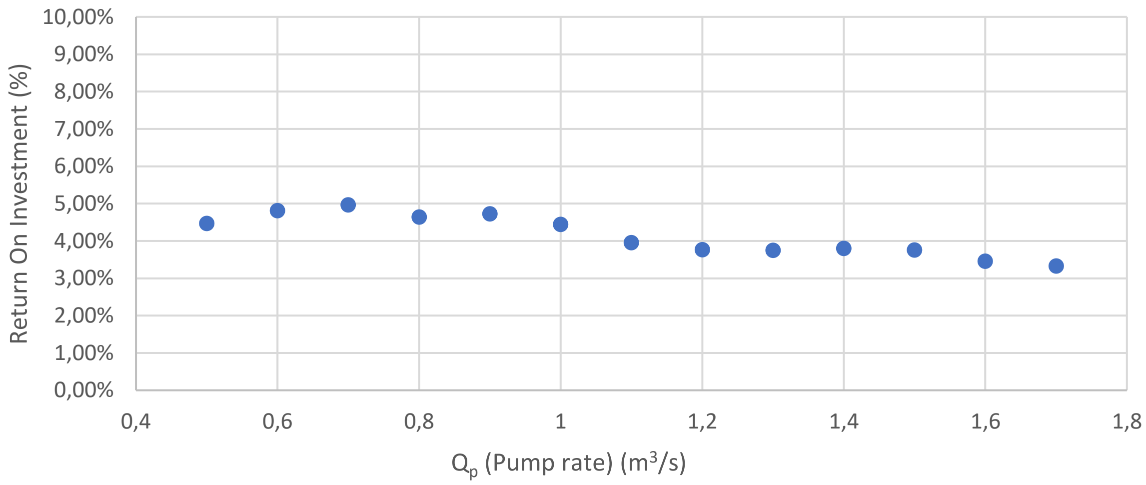

Figure 2 - Economic performance for a range of modelled pump rates at Dawlish study site

Conclusions and future work

The authors have explored the possibility of creating joint flood attenuation and energy storage assets to achieve dual benefits of storing electrical power and managing flood risk. This paper summarises development of the conceptual flood attenuation and energy storage model to evaluate viability at a site with dominant fluvial flood risk. The intent is to develop techniques to demonstrate the viability of these multi-functional water storage assets to enable flood risk management where it is not currently financially viable, with both fluvial and urban drainage applications proposed. The authors have demonstrated a potentially viable means to attract additional funding into flood risk management. The novelty of this research is derived through an exploration of dual benefit from controlling floods and provision of energy storage services. The outcome of this research shows modest financial returns can be generated that may support the provision of flood risk management in currently unviable locations.

The methodology described was based on parameter widely adopted in hydrological studies drawn from flood management literature. We propose to revisit the timeseries data and implement coding to collate publicly available datasets to enable repetition at other UK case study locations The success of this study provides justification for further investigation with the following priority research themes identified:

- Synthetic flood hydrograph integration into the methodology to broaden range of study sites
- Increased confidence in infrastructure costs suitable for a broader range of installation sizes
- Ascertain impact of head difference on PHFS performance and economic viability
- Testing of a broad range of catchment sizes to determine wider opportunity in lowland UK.

Acknowledgement

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