

Geographic information system algorithms to locate prospective sites for pumped hydro energy storage

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HIGHLIGHTS

- Developments of the “dry-gully” and “turkey’s nest” site models.
- A software “STORES” to locate prospective sites for pumped hydro energy storage.
- 190 sites identified in South Australia, with a storage capacity of 441 GL, 276 GWh.
- A comprehensive literature survey of Geographic Information System-based site searches.

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ABSTRACT

Pumped hydro energy storage is capable of large-scale energy time shifting and a range of ancillary services, which can facilitate high levels of photovoltaics and wind integration in electricity grids. This study aims to develop a series of advanced Geographic Information System algorithms to locate prospective sites for off-river pumped hydro across a large land area such as a state or a country. Two typical types of sites, dry-gully and turkey’s nest, are modelled and a sequence of Geographic Information System-based procedures are developed for an automated site search. A case study is conducted for South Australia, where 168 dry-gully sites and 22 turkey’s nest sites have been identified with a total water storage capacity of 441 gigalitres, equivalent to 276 gigawatt-hours of energy storage. This demonstrates the site searching algorithms can work efficiently in the identification of off-river pumped hydro sites, allowing high-resolution assessments of pumped hydro energy storage to be quickly conducted on a broad scale. The sensitivity analysis shows the significant influences of maximum dam wall heights on the number of sites and the total storage capacity. It is noted that the novel models developed in this study are also applicable to the deployments of other types of pumped hydro such as the locations of dry-gully and turkey’s nest sites adjacent to existing water bodies, old mining pits and oceans.

1. Introduction

Photovoltaics (PV) and wind constitute approximately half of the world’s new generation capacity installed in 2014–16. At the end of 2016, the global installations of PV and wind were beyond 300 gigawatts (GW) and 480 GW respectively [1,2]. Rapid growth of PV and wind energy in the electricity sector is expected to continue, driven by a broad range of issues associated with climate change, energy security and economics.

High shares of intermittent PV and wind energy in electricity grids bring significant challenges to the economics and security of the system as is the case in South Australia (SA), where nearly half of the state’s electricity production come from rooftop PV and wind farms [3]. SA has a low level of interconnection with the rest of the Australian

National Electricity Market (NEM) and there is no existing hydroelectric or pumped hydro facility established within the region. This brings significant challenges to power system operation and the state’s energy security due to supply intermittency and lack of sufficient inertial energy to support PV and wind electricity, especially in light of continuing rapid growth of PV and wind energy investment. In July 2016, when upgrades to the Heywood interconnector coincided with low wind generation at peak times, the average wholesale electricity prices in SA surged to \$229/MWh (Australian dollars per megawatt-hour) with 3 extreme price events on 7, 13 and 14 July beyond \$5000/MWh [4]. By contrast, the long-term average price in SA when the interconnector is available to import brown coal electricity from Victoria is \$50/MWh. Additionally, a range of system events such as load shedding and islanding occasionally occurred in 2016–17 [5,6]. This included a

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state-wide blackout on 28 September 2016, when three 275 kilovolts (kV) backbone transmission lines were damaged by a major storm event [7].

Pumped hydro energy storage (PHES) is capable of large-scale energy time shifting and a range of ancillary services such as frequency regulation, which can facilitate high levels of photovoltaics and wind integration in electricity systems. Developments of PHES began in the 1890s and surged through the 1960s, 70s and 80s in Europe, the United States and Japan where the rapid growth of nuclear energy and coal-fired units continued. These large thermal steam plants lack sufficient operational flexibility to accommodate changing demand and required the capability of load levelling. PHES was also regarded as a more economical alternative to oil and natural gas-fired plants for peak shaving, especially during the post-periods of energy crisis in the 1970s [8,9]. In recent years, the prosperity of PV and wind developments has led to a resurgence of interest in PHES. Open-loop PHES, which is continuously connected to a naturally flowing water feature [10], dominates the deployment of existing PHES. However, developments of conventional river-based hydroelectric including PHES are usually constrained by the availability of water resources and a variety of environmental concerns such as the interactions with ecology and natural systems [11]. Consequently, expansions of pumped hydro were generally not included in many high renewables future studies such as [12–14]. By contrast, short-term off-river PHES, which incorporates closed-loop pumped hydro systems, consumes modest amounts of water and has little impacts on the environment and natural landscape.

Recent studies [15,16] from the Australian National University show Australia can build an affordable and reliable electricity network with 100% renewable energy, using PV, wind, existing hydroelectric and biomass with the support of short-term off-river PHES. Preliminary Geographic Information System (GIS)-based works [15,17] suggested a large potential for off-river PHES to be deployed in the extensive hills and mountains close to population centres from North Queensland down the east coast to South Australia and Tasmania. This study focuses on the development of a series of advanced GIS algorithms which are capable of:

- Highlighting promising regions for PHES developments from a large region such as a state or a country, which can facilitate the planning of renewable energy development zones incorporating PV, wind, PHES and high-voltage direct current (HVDC) transmission.
- Rapid identification of prospective PHES sites with different characteristics of topography. For example, pairs of medium-sized reservoirs (dozens or hundreds of hectares) can be built on large flat lands as turkey's nest dams or located in enclosed dry gullies.
- Selection of optimal locations by ranking the sites identified from site searching on the basis of topography suitability and land use classes. Additionally, detailed site information such as the volumes of reservoirs, dam wall heights and lining areas will be helpful to integrate a costing tool in the next level of study.

Section 2 is a brief summary of the reviewed GIS-based studies on locating sites for the development of hydroelectric/PHES projects. Section 3 describes the mathematical models developed in this study. Section 4 outlines the GIS algorithms used to identify two different types of PHES sites. Section 5 illustrates the results from site searching by applying the models and algorithms introduced in Sections 3 and 4 to South Australia.

2. Literature review

PHES is a mature technology of large-scale energy storage. At the end of 2016, there were over 160 GW (rated power) of PHES in operation around the world with more than 85% of the installations deployed in Europe (> 50 GW), China (32 GW), Japan (26 GW) and the United States (23 GW) [18]. Recent studies on PHES focus on:

- Its significant roles as large-scale energy storage to facilitate large fractions of variable renewable energy integration while maintaining system reliability and security [19–21]. Our NEM and Western Australian studies [15,16] also demonstrated that energy affordability can be maintained in a system dominated by PV, wind, PHES and HVDC transmission.
- Operation strategies to maximise profits from energy arbitrage in competitive electricity markets and providing inertial response and ancillary services such as frequency control [22–24].
- Analyses of mechanisms and policy reform in electricity markets to facilitate development of PHES which is typically capital intensive and has a long lead time [25–28].
- Seawater and underground PHES which have minimum environmental impacts to ecology systems [29–33].
- Modern adjustable-speed PHES with wide operating ranges and higher efficiency, as well as improved dynamic stability under grid disturbances [34].
- GIS-based siting to locate sites by utilising contemporary advanced GIS and remote sensing technology.

2.1. GIS-based siting

Developments of advanced GIS and remote sensing techniques in recent years allow efficiency and accuracy improvements in the assessments of hydroelectric and water supply schemes such as computerised site identification utilising high-resolution digital elevation models (DEM). Table 1 is a brief summary of the reviewed GIS-based studies on hydroelectric/PHES site searching.

A number of studies focused on small hydro with power capacities ranging from hundreds of kilowatts (kW) to dozens of megawatts (MW), including both run-of-the-river and storage types of hydroelectric generation. Larentis et al. [35] developed a computerised “Survey & Selection” methodology for the evaluation of small run-of-the-river and storage hydroelectric systems within a river basin of Brazil. The study included a section-by-section analysis of dam and powerhouse locations and flow regulation and at-site optimisation for the assessment of total hydropower potentials of the basin. Kusre et al. [36] conducted a GIS-based site location with hydrological analyses for small run-of-the-river hydroelectric in northeast India by searching upstream from the outlet of a watershed to the fifth order of streams at an interval of 500 m. Yi et al. [37] undertook a cell-by-cell analysis to identify potential small hydro sites along rivers and a scoring system was established in the modelling, incorporating a variety of issues including topography, hydrology and environmental impacts. Petheram et al. [38] also examined the opportunities for developing water supply schemes with a minimum catchment area of 10 square kilometres (km²) in northern Australia.

For PHES, most studies concentrated on examining opportunities for existing waterbodies to be utilised as upper and/or lower reservoirs of PHES systems. This includes the investigation of existing artificial reservoirs belonging to hydroelectric or water supply schemes as well as natural lakes as greenfield projects. Hall & Lee [39] investigated the potentials of utilising existing waterbodies in close proximity to hydroelectric or water supply schemes to serve as open-loop PHES reservoirs on the basis of 4 critical criteria (capacity, area, distance and elevation difference) derived from the characteristics of 43 existing PHES in the contiguous United States. Gimeno-Gutierrez & Lacal-Arantequi [40] investigated the potentials of matching pairs of existing reservoirs as PHES facilities within distances of 1–20 km (elevation difference > 150 m) across 31 countries of Europe, where thousands of sites were identified with a realisable storage capacity of 29 terawatt-hours (TWh), especially in Turkey, Spain and the Alps countries. Jimenez Capilla et al. [41] demonstrated a multi-criteria GIS-based analysis of site selection for an existing dam to be retrofitted into PHES systems, which incorporated the aspects of topography, land use, geology and meteorology by applying the analytic hierarchy process into a decision model. Fitzgerald et al. [42] investigated the adjacent

Table 1
A brief summary of the reviewed GIS-based studies on hydroelectric/PHES site searching.

Study	Region	Project type	Site type	Input datasets	GIS platform and processing time	Results	Ranking metrics	Cost model
Larentis et al. [35]	Taquari-Antas (26,500 km ²), Brazil	Small hydro	Run-of-the-river, storage	DEM 90 m, Hydro, PA	ArcGIS & Fortran	997 sites, 736 MW	Products of head and slope	Not included
Küsrü et al. [36]	Umkhen watershed (1,204 km ²), India	Small hydro	Run-of-the-river	Topo 1:50,000, LU, Hydro, Meteo	ILWIS	107 sites on 9 streams, 133 MW	Not included	Not included
Yi et al. [37]	Bocheong stream basin (554 km ²), Korea	Small hydro	Run-of-the-river, storage with dam heights 5–20 m	DEM 30 m, LU, Hydro, PA	ArcView & Avenue (5 hours)	4 storage sites, 2 run-of-the-river sites	A scoring system	Not included
Petheram et al. [38]	Finniss and Adelaide catchments (16,950 km ²), Australia	Water supply	Earth embankment, roller compacted concrete	DEM 30 m, Hydro	GDAL modules & Python	Dozens of sites > 5 GL per \$m	Storage-cost and yield-cost ratios	A cost function
Hall & Lee [39]	Contiguous United States	PHES	Existing waterbodies	DEM 10 m, LU, PA, Res, Lakes	Unknown	2,505 sites	Capacity of base plants and head	Not included
Gimeno-Gutierrez & Lacal-Arantegui [40]	31 European countries	PHES	Existing reservoirs of hydroelectric and water supply projects	DEM 90 & 250 m, LU, PA, Res, Infra	ArcGIS & DIVA-GIS	Thousands of sites, 29 TWh (realisable)	Not included	Not included
Jimenez Capilla et al. [41]	Rules dam, Spain	PHES	Flatlands near existing water supply schemes	Topo, LU, Geo, Meteo, PA	ArcGIS	3 alternatives for Rules Dam	A decision (suitability) model	Not included
Fitzgerald et al. [42]	612 reservoirs in Turkey	PHES	Flatlands adjacent to existing reservoirs	DEM 90 m, Res, PA, Infra, LC	ArcGIS & ModelBuilder	444 sites, 3.8 TWh (realisable)	Largest energy storage capacity	Not included
Kucukali [43]	7 existing hydroelectric in Turkey	PHES	Flatlands adjacent to existing hydroelectric	Topo 1:25,000, LU, Geo, PA	Unknown	5 upper reservoirs 200–650 m	A suitability model	Not included
Lu & Wang [44]	Tibet (1.22 million km ²), China	PHES	Existing lakes and narrow valleys	DEM 30 m, Lakes, Grid	ArcGIS & ModelBuilder (hours)	558 sites, 4.3 TWh	Smallest slopes or minimum distances	Not included
Rogeanu et al. [45]	France (675,000 km ²)	PHES	Existing lakes and natural depressions	DEM 25 m, Topo, PA	RStudio & R (2–3 weeks)	1,145 pairs, 33 GWh	A virtual “cost of energy”	Not included
Connolly et al. [46]	Abbeyfeale (800 km ²), Ireland	PHES	Off-stream flatlands	DTM 10 m	Atlas SCC & C++ (6–10 days)	5 sites, 710–979 MW, 8,634 MWh	Not included	Not included

Note. GIS algorithms and search criteria of these studies outlined in Section 2 and 4. Acronyms and abbreviations: topography (Topo), hydrology (Hydro), geology (Geo), meteorology (Meteo), digital elevation models (DEM), digital terrain models (DTM), transmission network (Grid), infrastructure (Infra), land use (LU), land cover (LC), protected areas (PA), dams & reservoirs (Res), natural waterbodies (Lakes).

flat areas (with slopes of 0–5 degrees) of 612 existing reservoirs in Turkey, identifying over 400 sites with heads > 150 m and storage capacity > 1 gegalitre (GL), where the sensitivity of the number of sites, energy storage capacity and head to buffer distance (radius) was also studied. Similarly, Kucukali [43] established a suitability model for the multi-criteria assessment (scoring 1–3) of surrounding areas of existing hydroelectric projects to be exploited as PHES upper reservoirs. Lu & Wang [44] investigated existing lakes and natural narrow valleys that can be utilised for the development of large-head (> 500 m) PHES, where the site searching was conducted at an interval of 500 m on stream lines created to represent valleys.

Only a few studies investigated site identification for closed-loop off-stream PHES on a large scale. Rogeau et al. [45] investigated the opportunities for small-scale PHES in France (with a minimum storage capacity of 500 kW × 10 h) utilising existing waterbodies (lakes) and natural depressions as upper and lower reservoirs. A virtual “cost of energy” was used to rank the identified sites, which incorporated energy storage capacity and a range of cost components such as lining, water conveyance and grid connection in a scoring system. Connolly et al. [46] developed a Triangulated Irregular Network model searching for flatlands to locate PHES reservoirs, where the flatness of terrain was defined by the thresholds of maximum earthwork from cut and fill balancing.

2.2. Novelty of this work

Previous GIS-based studies such as [35–44] concentrated on river-based hydroelectric/water supply schemes or PHES systems based on natural lakes and existing artificial reservoirs. However, constructions of such generation or storage facilities are usually associated with a wide variety of environmental concerns such as the interactions with ecology and natural systems and the negative impacts on soils and geology [11]. By contrast, this study focuses on short-term off river energy storage (STORES), which refers to closed-loop PHES systems located away from rivers and thus has little environmental impacts. Environmental impacts of STORES facilities are further discussed in Section 4.5.

A significant feature of STORES is the large altitude difference between upper and lower reservoirs, typically > 300 m. Large hydraulic heads enable significant amounts of electricity to be stored in pairs of medium-sized reservoirs where the consumption of water is modest. For example, a PHES system with twin 100 hectares (ha), 1 gegalitre (GL) reservoirs separated by a height difference of 500 m is able to contribute 1 gigawatt-hour (GWh) of storage capacity (assuming an usable fraction of 85% and an efficiency of 90%), or 200 MW of power with 5 hours of storage to the electricity system - equivalent to a large gas-fired power plant.

Section 4.6 Access to water provides a brief introduction of the source of initial fills, as well as a variety of measures to mitigate evaporation and leakage losses.

In addition, a novel turkey’s nest site model is developed in this study. Conventional definitions of turkey’s nest sites were usually based on average surface slopes [42] or amounts of the earthwork required to flatten the sites [46]. While these approaches can highlight large flat lands with slight slopes, they may fail to identify those sites with larger slopes but still being desirable because the construction work for the dams is modest. This is detailed in Section 4.3 and examples are shown in Fig. 5. In this study, the turkey’s nest site model incorporates the calculations of dam volumes and dam wall heights, which have significant influences on the economics of PHES systems, and hence can effectively reflect the suitability of the sites.

Dry-gully sites impound a reservoir by utilising existing terrains as a major part of the dam. The lack of efficient GIS algorithms for dry-gullies has constrained the assessments of PHES potentials on a broad scale, as well as limiting the accuracy of the modelling results. Lu & Wang [44] used approximations (a triangle pyramid) to represent

narrow valleys. Rogeau et al. [45] matched existing waterbodies (lakes) and terrain depressions, where the storage capacities only ranged from megawatt-hours (MWh) to hundreds of MWh (compared with GWh-scale in this study). In this study, an improved dry-gully model is presented, which incorporates a series of advanced GIS algorithms such as: (1) distributions of a large number of pour points on a virtual stream network which allows high-resolution (10 m) site searches to be conducted along the “streams” where the dry-gully sites are more likely to be located and, (2) delineation of reservoirs and dams in a watershed model, which enables PHES facilities to be visualised in three dimensions (Fig. 10).

Furthermore, the automatic GIS-based procedures provide a powerful mapping tool, the software “STORES”. “STORES” can highlight the most promising regions for PHES deployments and efficiently identify the optimal PHES sites in terms of high water to rock (W/R) ratios i.e. large reservoir volumes with less earthwork. A range of detailed site information such as surface area and volume are also produced from the modelling. The development of the software “STORES” facilitates high-resolution site searches across a large land area which are typically computationally intractable. This allows a rapid estimate of PHES potentials to be conducted within a state or a country as demonstrated in Section 5.

It is noted that although fresh-water PHES is the focus of this study, the dry-gully and turkey’s nest site models are also applicable to the deployments of other types of pumped hydro.

3. Models for potential PHES sites

The direct cost of constructing a PHES facility can be broken down into two major components:

- Power components including the machinery parts such as turbines, generators, transformers and switchyards, the costs of which are in proportion to or associated with the power rating (MW) of PHES and expressed in terms of dollars per kilowatt (\$/kW). Water conveyance facilities between upper and lower reservoirs are also included in this category as its size decides the flow rate and hence determines the power capacity.
- Storage components, which are related to the storage capacity (MWh) of a plant consisting of such as dams, earth excavation and lining costs, expressed in terms of dollars per kilowatt-hour (\$/kWh).

While a wide range of factors such as geology and hydrology are involved in site selection and dam construction, the topography of a site is always a critical issue which decides the type, height and shape of a dam, as well as the amount of earthwork required to build it. In this study, two types of terrain are considered to be of high priority in site selection in terms of topography fitness for the deployment of short-term off-river PHES: dry-gully (DG) sites and turkey’s nest (TN) sites. The definition of DG and TN sites is in line with the T2, T3 types of PHES in European studies [47]. The TN and DG models outlined as follows were developed with experienced hydro and civil engineers from Australia and New Zealand.

3.1. Dry-gully sites

A dry-gully site features a gentle gully located near the top of a hill, which is capable of impounding a certain amount of water by utilising existing terrain as a major part of the dam. A typical example of this type of site is the upper reservoir of Presenzano Hydroelectric Plant in Italy (Fig. 1).

A notional model for the DG sites is established as shown in Fig. 2, where the terrain of a location at latitude -32.116638 , longitude 137.987237 is used as a prototype. V_{res} and A_{res} represent the volume and the surface area of a reservoir while V_{dam} , B_{dam} and $H_{dam,max}$

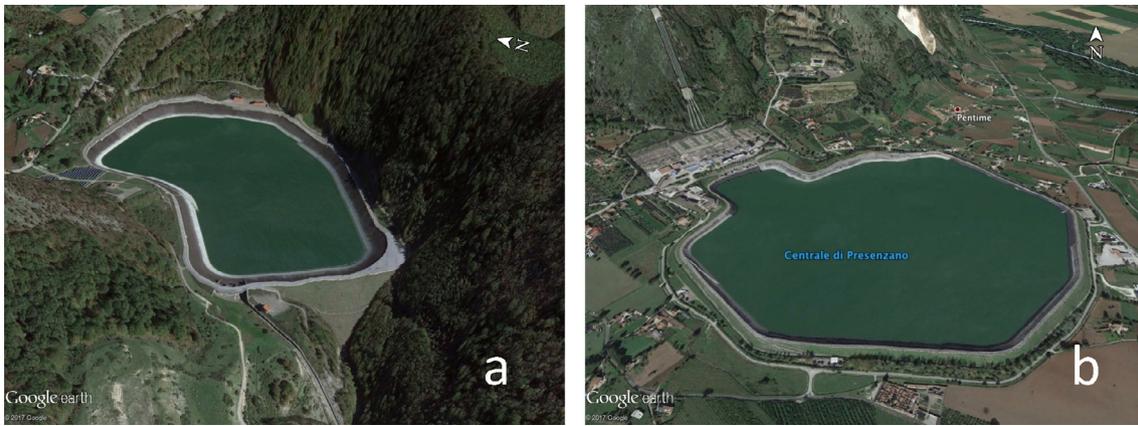


Fig. 1. Upper (a) and lower (b) reservoirs of Presenzano Hydroelectric Plant, Italy (elevation exaggeration: 3).

denote the volume of earthwork required to build a dam, the dam’s batter ratio and maximum wall height.

Dam batters of typical earth dams in USACE [48] range from 1:2–1:4 (downstream) and 1:2.5–1:4.5 (upstream) while for rock-filled dams, it is in the range of 1:1.6–1:2. Similarly, Mai [49] suggested 1:2.5–1:3.5 (upstream), 1:2–1:3 (downstream) for earth dams and 1:1.4–1:1.7 for rock-fill dams. For concrete dams, it is in the range of 1:0.7–1:0.8 [50]. In this study, the dams of the DG sites are assumed to be rock-fill or concrete with a batter of 1:1 while for the TN sites (Section 3.2) where the dam heights are typically lower than the DG sites, an earth-filled embankment dam with a batter of 1:3 is assumed. This assumption allows a rapid screening for DG and TN sites across a large land area and will be subject to optimisation when a specific site is chosen for feasibility study and engineering design.

3.2. Turkey's nest sites

A TN site is located on relatively flat land, which can be enclosed by a surrounding earth-filled embankment dam to store a certain amount of water. The lower reservoir of Presenzano Hydroelectric Plant in Fig. 1 is an example of the TN sites. Fig. 2 illustrates the model of TN sites developed in the study, where the definition of parameters remains the same with Section 3.1.

3.3. Equations

$$V_{res} = V_{org} + \frac{V_{dam}}{2} \tag{1}$$

$$V_{org} = A_{res} \frac{\sum_{i=1}^m (E_{dam} - E_i)}{m} \tag{2}$$

$$V_{dam} = L_{dam} B_{dam} \frac{\sum_{j=1}^n (E_{dam} - E_j)^2}{n} \tag{3}$$

$$E_{dam} - E_i \geq 0, E_{dam} - E_j \geq 0 \tag{4}$$

$$H_{dam,max} = E_{dam} - E_{j,min} \tag{5}$$

Eqs. (1)–(5) demonstrate the calculations of the volume of the reservoir, V_{res} , and the maximum dam wall height, $H_{dam,max}$, where L_{dam} represents the dam’s crest length; E_i and E_j represent the elevations for the i_{th} cell of the reservoir and the j_{th} cell of the dam while E_{dam} denotes the elevation of the dam crest; m and n are the total numbers of raster cells within the reservoir and dam respectively. Eq. (1) assumes the soils or rocks required to build the dam are obtained from excavation within the reservoir area and hence adds half of the dam volume $V_{dam}/2$ to the total volume of reservoir. V_{org} is the volume impounded by original terrain of the site (i.e. prior to excavation), where the thickness of dam is assumed to be zero. Eq. (3) is a simplified form of dam volume calculation, where freeboard and dam crest width (decided in detailed engineering design) are not factored in. A full equation of dam volume calculation, which incorporates freeboard height and dam crest width,

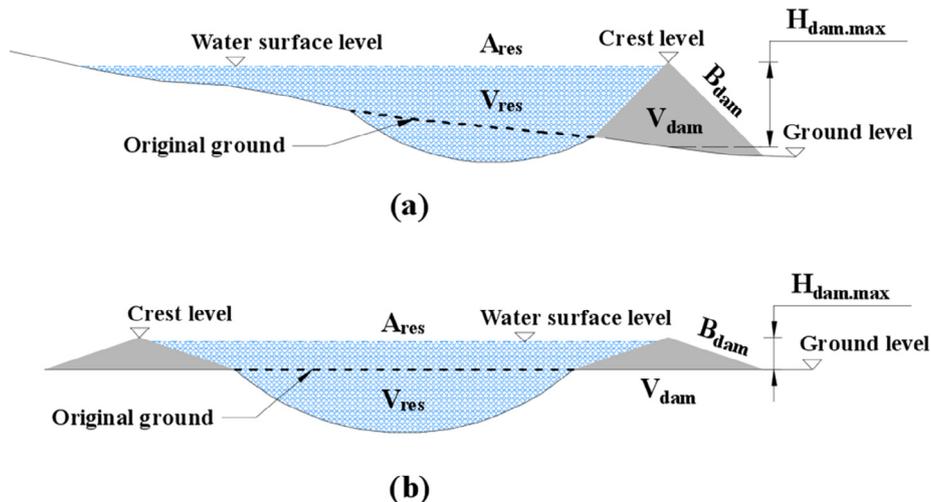


Fig. 2. Cross sections of typical dry-gully (a) and turkey's nest (b) sites.

is included in Appendix A.

3.4. Other types of PHEs sites

Due to the long-term prosperity of mining activities in Australia, there are a large number of old mining pits likely to be converted into PHEs systems such as the proposed Kidston Pumped Storage project in northern Queensland [51]. Opportunities for retrofit of existing hydroelectric schemes also exist (though it is limited) such as in the Snowy Hydro scheme and in Tasmania, an island state with over 90% of electricity from hydro resources [52,53]. Furthermore, a seawater PHEs facility is being studied which is located at the top of Spencer Gulf of SA [54] though there are a number of challenges in the development of ocean-based PHEs [17]. The models established in Section 3.1, 3.2 and the GIS algorithms outlined in Section 4 can be used for site searching within the regions for mining pits, existing reservoirs, as well as near ocean sites.

4. GIS algorithms

A software named STORES is developed in the modelling which includes the following functional modules (Fig. 3):

- “Highlight” to exclude the regions without sufficient altitude difference within an acceptable distance
- “DryGully” to identify DG sites within the highlighted areas
- “TurkeysNest” for the identification of TN sites within the highlighted areas
- “PrettySet” for the optimisation of site selection

All of the scripts are written in Python and using its libraries such as NumPy and SciPy, as well as the ArcPy package from Esri ArcGIS.

4.1. Highlighting promising regions

In order to reduce computation loads which are associated with the search scope, an exclusion criterion is applied to exclude the regions without the height differences required for efficient storage. A threshold of minimum head to horizontal distance (H/D) ratio is used to highlight the regions that meet the criterion. A minimum H/D ratio of 1:10 was used in [43–45,55]. In this study, a moderate relaxation of the ratio (1:15) is assumed to include those sites with a ratio slightly lower than 1:10. Additionally, protective areas and intensive land uses are excluded at this procedure to allow elimination of any conflict or competition with the regions which are sensitive to environmental impacts and social acceptance.

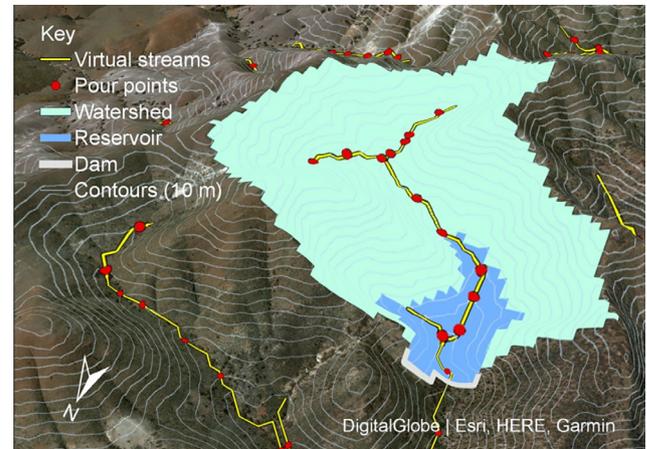


Fig. 4. Delineation of the watershed, reservoir and dam of a dry-gully site (elevation exaggeration: 2).

Detailed information of the results from applying this approach to the DEM of the case study region, South Australia, is demonstrated in Section 5.2.

4.2. Identifying dry-gully sites

To identify potential dry-gully sites as defined in Section 3.1, a virtual stream network is derived from the void-filled DEM. A threshold minimum of 111 accumulation cells is set in the delineation of virtual streams to allow the surface area of reservoir to be greater than 10 ha at the cell resolution of approximately 30 m. Lu & Wang [44] also extracted a virtual stream network from the DEM to identify natural valleys that can be utilised as a PHEs reservoir. Different from Lu & Wang [44], this study calculates the storage capacity of dry gullies and the required earthwork to build a dam through a watershed model (Fig. 4).

Then, for raster cells at an interval of 10 m height on the virtual stream network, a sequence of virtual pour points are created by extracting intersections of the streams and the 10 m contours (Fig. 4). A watershed is calculated for each pour point from its location and a flow direction raster derived from the DEM.

Maximum dam wall heights are then used to define the flooded areas (reservoirs) within that watershed. A minimum surface area of 111 raster cells (around 10 ha) is applied again at this step to ensure the reservoirs selected for further analysis are capable of a sufficient storage capacity. In addition, the pour points located on a slope greater than 1:5

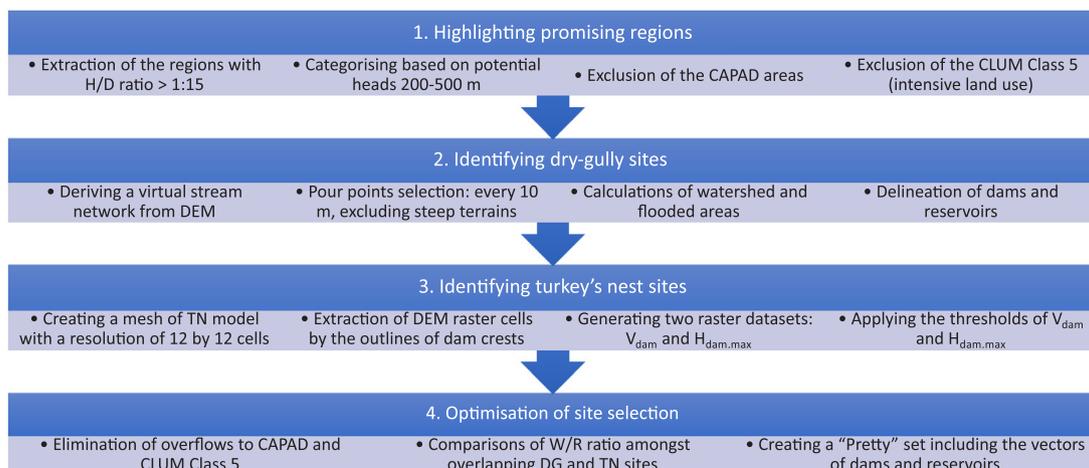


Fig. 3. GIS-based procedures for pumped hydro site searching.

are excluded due to the likelihood of insufficient storage capacity. Moreover, it avoids dam construction on steep terrain which is only technically feasible under limited conditions [48].

A cell-by-cell or section-by-section analysis along a stream network is a generic approach for decision making in the planning of hydroelectric or water supply schemes such as [35] and [38]. By specifying a maximum height of dam wall at the location of each pour point, the flooded areas, which includes all the raster cells of watershed with an altitude difference less than the maximum dam wall height from the pour point, can be decided. The outline of a dam is then delineated from the common edges (cells) of the watershed and its corresponding flooded areas (reservoir) as shown in Fig. 4.

4.3. Identifying turkey's nest sites

While the GIS algorithms outlined in Section 4.2 are capable of a quick identification of DG sites as shown in Section 5.3, a different approach is needed to identify the second type of PHES site, turkey's nest, as defined in Section 3.2. This is needed due to the different characteristics of TN sites.

- A TN site usually incorporates a broader surrounding flat areas than a single watershed in order to increase the storage capacity while reducing dam wall heights.
- For lower reservoirs, a TN site is usually preferred to facilitate the construction of the underground powerhouse closer to the upper reservoir to reduce the penstock or tunnel length

Generally, flat land or a natural depression is preferred for the dam construction at TN sites as local terrain characteristics determine the maximum dam wall height and the required earthwork to build a dam. On flat land (slope = 0) for example in Fig. 5, a dam height of 15 m with an impoundment area of 5 ha is capable of storing 1 GL of water while $H_{dam,max}$ reduces to 13 m on a “depression”-like terrain with an average slope of 15%. By contrast, a “slope”- or “rise”-like topography with an average slope of 15% requires greater $H_{dam,max}$ (17–25 m) and a greater V_{dam} (635–650 megalitres, ML) to store 1 GL of water.

As shown in Fig. 5, the maximum dam wall height and the earthwork required to build a dam to store 1 GL of water are heavily influenced by the topography and hence either $H_{dam,max}$ or V_{dam} can be a guide to reflect the appropriateness of the terrain to build TN dams. Connolly et al. [46] developed a similar approach calculating maximum allowable earthworks to reflect the flatness of terrains whereas in this study, V_{dam} and $H_{dam,max}$ are used to assess the suitability for a TN dam

Table 2
Search criteria.

Criterion	Dry-gully sites	Turkey's nest sites
Minimum head to distance ratio	1:15	1:15
Minimum head	300 m	300 m
Minimum surface area of reservoir	10 ha (111 raster cells)	5 ha
Minimum storage capacity	1 GL	1 GL
Maximum dam wall height	40 m	20 m
Maximum excavation	–	600 ML
Dam batter	1:1	1:3
Maximum slope for dam construction	1:5	–
Protected areas	Not in CAPAD	Not in CAPAD
Intensive land uses	Not in CLUM Class 5	Not in CLUM Class 5
Resolution (Searching interval)	10 m height	12 cells × 12 cells

construction. Consequently, two raster datasets of $H_{dam,max}$ and V_{dam} are created by using the TN model established in Section 3.2. The cell size of the $H_{dam,max}$ and V_{dam} rasters is approximately 360 m × 360 m to incorporate the TN model in the data. After the $H_{dam,max}$ and V_{dam} rasters are created, a threshold of $H_{dam,max}$ or V_{dam} can then be applied to select out most promising TN sites.

The search criteria used in the modelling are listed in Table 2.

4.4. Optimisation of site selection

In the previous procedure, overlaps of identified DG sites cannot be avoided since the sites searching is at a vertical interval of 10 m while the maximum dam wall height is 40 m. Consequently, a ranking metric is needed to highlight the most promising sites. As summarised in Table 1, a variety of ranking metrics such as head, storage capacity or cost of energy can be used to rank the sites highlighting the most promising locations. In this study, a W/R ratio is used to select optimal sites with larger water capacity relative to the amount of earthwork when overlaps occur. The W/R ratio is defined as the water storage capacity divided by the earthwork required to build such a reservoir/dam capable of this storage capacity.

It is noted that, in some cases, a DG site with a higher elevation and hence a larger potential head may not be competitive with a lower site which has a larger W/R ratio. So before the optimisation algorithm is applied, a “Master” set is established including all the identified sites in site searching, which allows an optimisation on the basis of cost per unit of storage capacity (\$/kWh) can be considered when cost models

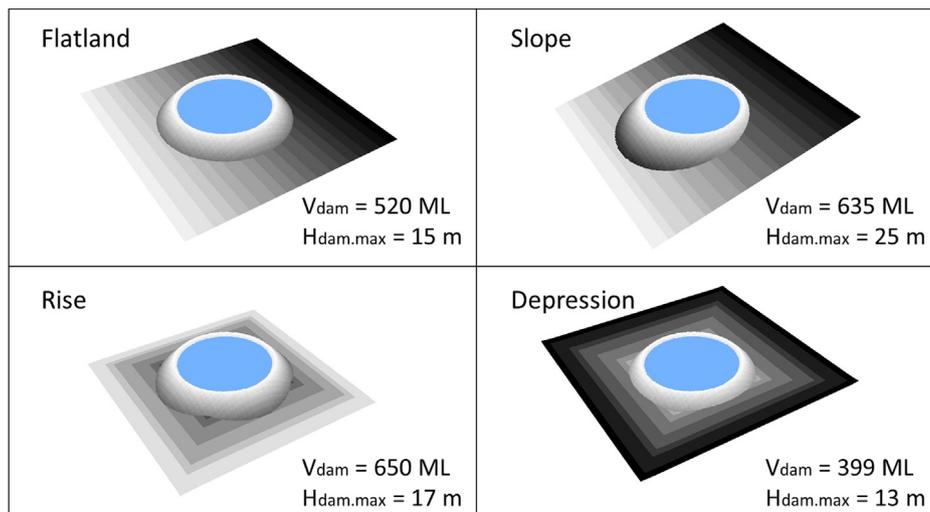


Fig. 5. Excavation for dam construction (V_{dam}) and maximum dam wall height ($H_{dam,max}$) under 4 typical terrains to store 1 GL of water (elevation exaggeration: 3).

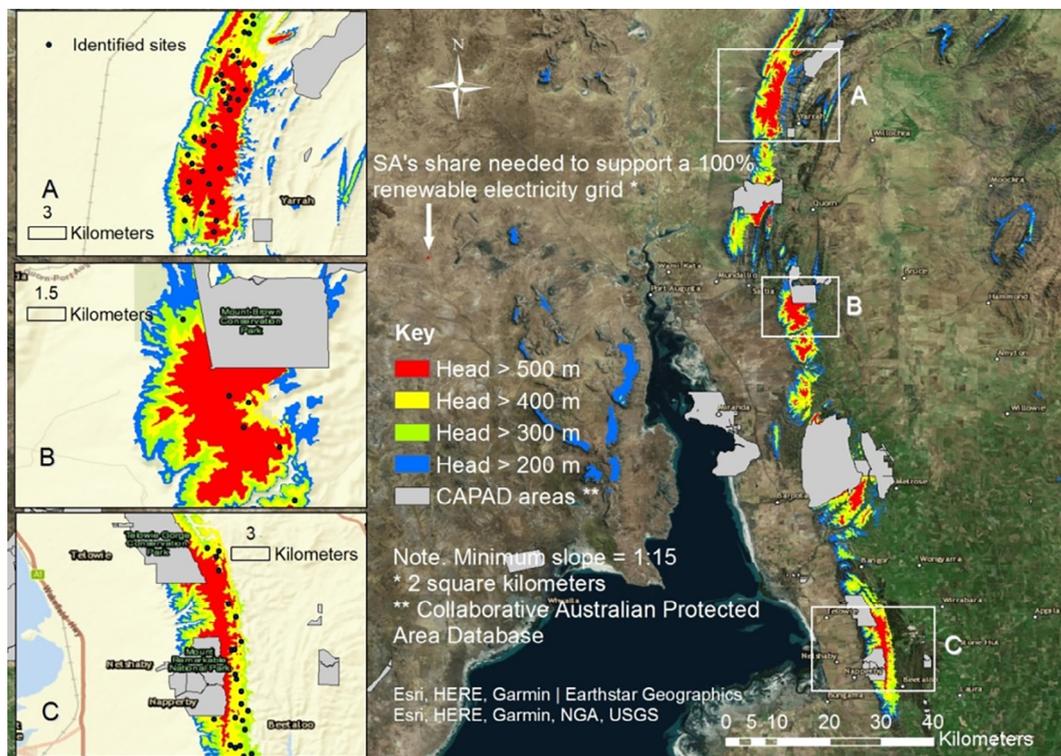


Fig. 6. Highlighted promising regions for off-river pumped hydro in the Flinders Ranges, east of the upper Spencer Gulf near Port Augusta.

are integrated in a future study.

4.5. Environmental impacts

Unlike conventional river-based hydroelectric projects, STORES is located away from rivers and has little impacts on the environment and natural landscape due to: (1) no interaction with the ecosystem of main stem rivers, (2) no conflicts or competition with nature reserves and intensive land uses and, (3) medium-sized reservoirs located within close proximity to electricity infrastructure and renewable energy resources.

Wänn et al. [11] demonstrated that closed-loop PHES systems have lower impacts on soils, geology & sediment transport and have moderate impacts on water resources & quality compared with conventional pump-back or semi-open PHES facilities. The environmental assessment report released by the Federal Energy Regulatory Commission for the proposed Gordon Butte Pumped Storage Hydro Project in Montana, the United States concluded that there will be no significant environmental impacts in constructing and operating the project. Temporary, short-term effects during the constructions can be further mitigated by a variety of environmental management measures.

Detailed environmental impact assessment, which includes the assessments of human interaction, ecology and natural systems and physical environment, will typically be conducted in the engineering feasibility study of any specific sites. This is beyond the scope of this study which is only focusing on the development of GIS algorithms.

4.6. Access to water

Pairs of medium-sized reservoirs mean STORES facilities consume much less water (as explained in Section 2.2) compared with conventional river-based hydroelectric projects. Typically, the initial fill to initiate the facilities is either conveyed from nearby water sources such as from existing reservoirs or lakes, or collected by creating on-site micro-catchments. During operation, the imbalance between rainfall and losses due to evaporation and leakage can be supplemented by the

micro-catchments, groundwater, or by trucked water depending on local availability.

For example, the initial fill of the proposed Coffin Butte Pumped Storage (20 ha, 3 GL) in Montana, the United States is obtained by a temporary diversion on Miller Creek and the loss of evaporation and leakage is supplemented by groundwater. The Kidston Pumped Storage project, which will utilise the abandoned gold mines in Queensland, Australia as upper (52 ha) and lower (54 ha) reservoirs, has access to the existing Copperfield Dam previously built for mining activities.

Additionally, despite the evaporation issues are site-specific, they can generally be mitigated by various evaporation reduction measures such as floating covers which have a claimed reduction efficiency of 90%.

5. Case study

5.1. Input datasets

1 arc-second DEMs for South Australia are downloaded from the United States Geological Survey's Long Term Archive. Given the surface area of a typical short-term off-river PHES facility ranges from 10 to 100 ha, the resolution of DEM (approximately 30 m) is well suited, where a typical reservoir contains 100–1000 raster cells. The Collaborative Australian Protected Area Database (CAPAD) and the Catchment Scale Land Use (CLUM) datasets, available from the Australian Department of the Environment and Energy and Department of Agriculture and Water Resources respectively, include the information of protected areas and intensive land use classes, which are considered to be not suitable for the construction of PHES. High-voltage transmission lines (> 132 kV) data are derived from the National Electricity Transmission Lines dataset developed by Geoscience Australia.

The coordinate systems of all the datasets in this study use or are projected to the GCS WGS 1984 as well as the GDA 1994 Geoscience Australia Lambert which is used for the calculation of reservoir surface area and dam length.

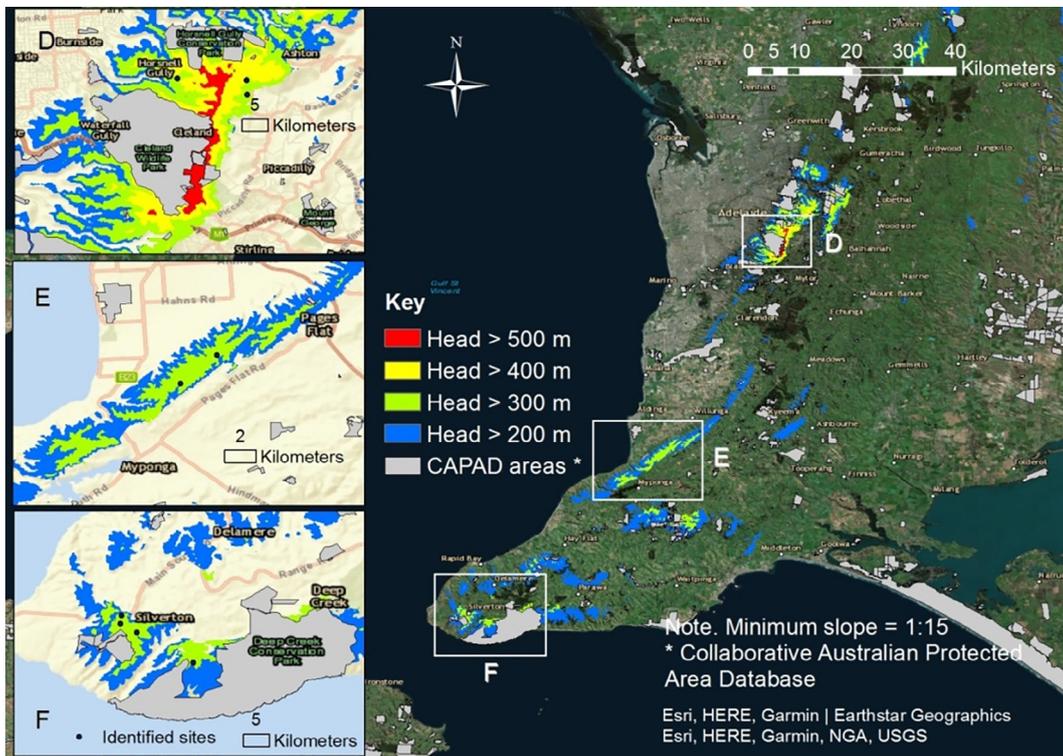


Fig. 7. Highlighted promising regions for off-river pumped hydro in Mount Lofty and the Fleurieu Peninsula near the capital city, Adelaide.

5.2. Promising regions

South Australia has a land area of 983,482 square kilometres [56]. By applying the models described in Section 3 and the algorithms outlined in Section 4, together with a range of search criteria listed in Table 2, a GIS-based screening was conducted across SA. Figs. 6 and 7 show two promising regions of SA highlighted from the modelling constituting 0.1% of the land area of the state:

- Flinders Ranges, east of the upper Spencer Gulf near Port Augusta and,
- Mount Lofty and the Fleurieu Peninsula near the capital city, Adelaide.

Each location of these regions has a H/D ratio greater than the threshold defined in Table 2. A minimum H/D ratio of 1:15 is used on the basis of the previous engineering experiences as discussed in Section 4.1, while any other values that users desire can be specified. Potential locations for upper reservoirs are denoted by multiple colours according to the different hydraulic heads. It shows a large potential of off-river PHES in SA, especially compared with the amount of storage required in SA to support a 100% renewable electricity grid in Australia [15].

As shown in the figures, the CAPAD areas have been excluded to ensure the sites are outside national parks. It is noted that while freshwater, large-head PHES is recommended in this study as discussed in Section 2.2, potential seawater PHES sites can also be identified from the modelling such as the project proposed for the upper Spencer Gulf [54].

5.3. Identified dry-gully sites

Promising regions with potential heads greater than 300 m are further analysed to identify DG sites as well as TN sites illustrated in Section 5.4.

As shown in Fig. 8, the searching scope within South Australia

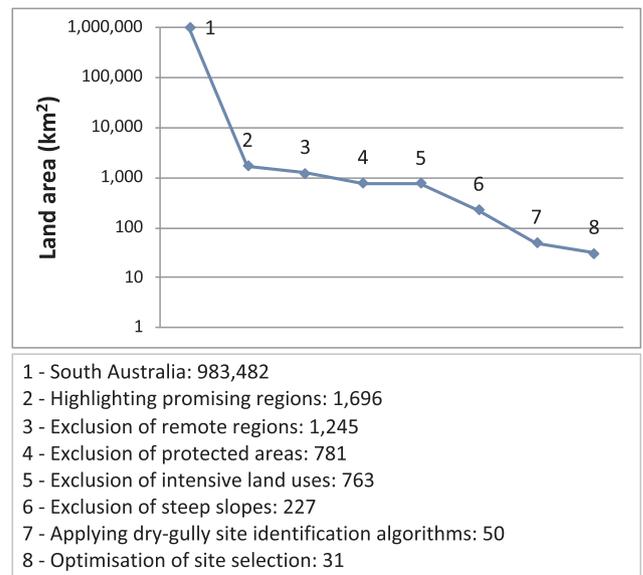


Fig. 8. Evolution of the searching scope within South Australia by applying the GIS-based site searching algorithms.

reduces from nearly 1 million to 31 km² after applying a sequence of GIS-based procedures including the exclusion of remote regions, CAPAD, CLUM Class 5 and slopes > 1:5. A total of 423 DG sites, which satisfy the criteria listed in Table 2, are identified from the searching algorithms and 168 are included in the final set by excluding overlapping reservoirs with lower W/R ratios. Dots shown in the insets of Figs. 6 and 7 represent the exact locations of DG sites included in the final set within those regions.

A snapshot of site information such as storage capacity and dam length is shown in Fig. 9, while a full collection of the identified DG sites is included in Appendix B. A promising DG site located at latitude –32.116638, longitude 137.987237 is shown in Fig. 10 by 3-

	A	B	C	D	E	F	G	H	I	J	K
1	Index	Latitude	Longitude	Elevation (m)	Water area (ha)	Ground area (ha)	Reservoir volume (GL)	Dam length (m)	Dam area (ha)	Dam volume (GL)	Water-rock ratio
2	RES_1	-35.6322222	138.1994444	303	9	9	2	1812	5.1	0.7	3
3	RES_8	-35.6149537	138.167037	309	19	19	3	2617	5.3	0.5	6
4	RES_11	-35.61	138.1577778	310	40	40	7	3260	6.2	0.6	12
5	RES_12	-35.4615278	138.5509722	350	15	15	3	2238	5.7	0.7	5
6	RES_19	-35.4547222	138.5213889	369	10	11	1	1754	3.6	0.4	5
7	RES_20	-35.4539811	138.5427778	371	9	9	1	1645	3.2	0.3	4
8	RES_21	-35.4536111	138.5493522	362	8	9	2	1594	5.3	0.9	3
9	RES_29	-35.4391667	138.5597222	360	11	11	2	1807	3.8	0.4	6
10	RES_38	-35.3431944	138.4938889	322	90	91	12	3019	5.7	0.5	23
11	RES_46	-35.3268056	138.5148611	330	12	13	3	1964	4.8	0.6	5
12	RES_87	-34.9527778	138.7266667	530	23	23	3	1404	2.9	0.3	12
13	RES_102	-34.9477083	138.7263194	542	15	15	3	1342	3.9	0.6	5
14	RES_106	-34.9469444	138.7026389	449	9	10	1	347	1.2	0.2	9
15	RES_139	-34.9152778	138.7997222	543	11	11	2	1482	3.6	0.4	6

Fig. 9. A snapshot of detailed information on the identified sites.

dimensional visualisation of the dam and reservoir in ArcGIS Pro.

The sensitivity of the total storage capacity and the number of sites to the maximum dam wall height is examined by varying the height from 10 m to 80 m as illustrated in Fig. 11. Dams of the Snowy Mountains Scheme in Australia range from 18.3 to 116.5 m (earth-fill), 43.9–161.5 m (rock-fill) and 21.3–86.3 m (concrete gravity/arch) with gross capacities of 21.1–4798.4 GL [57].

5.4. Identified turkey’s nest sites

As stated in Section 4.3, the maximum dam wall height of a TN site, $H_{dam,max}$, and the required earthwork to build it, V_{dam} , are heavily influenced by the topography of that site. Fig. 12 illustrates the distributions of V_{dam} and $H_{dam,max}$ within the promising regions (head > 300 m) and Fig. 13 shows their relationships with the standard deviation $E_{res,std}$ and range $E_{res,ring}$ of elevation as well as the average slope $S_{res,avg}$ in degrees. In this study, a maximum dam wall height of 20 m and a maximum excavation volume of 600 ML are used to highlight the optimal TN sites as illustrated in Fig. 12, which represents 0.2% and 7.8% percentiles respectively. In addition, the thresholds of $H_{dam,max}$ and V_{dam} can be specified by users as search criteria.

Finally, 22 TN sites were identified with a total area of 110 ha and a volume of 22 GL by applying the search criteria listed in Table 2. At some locations, the sites identified by the two different algorithms may have overlapping sections and in this case, the W/R ratio is once again applied to decide the most promising sites with larger storage capacity while less required earthwork. A final set of the TN sites is included in Appendix B.

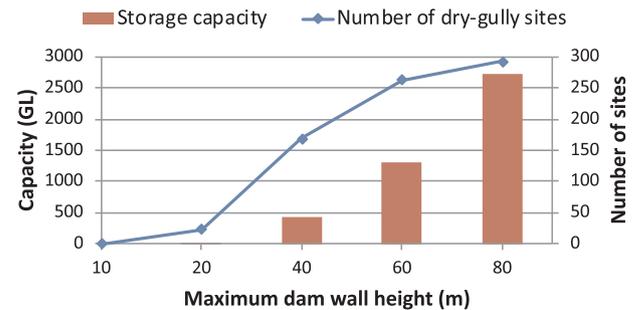


Fig. 11. Sensitivity of the total storage capacity (GL) and the number of sites to the threshold of maximum dam wall height (10–80 m).

6. Conclusion and future work

Grid-scale storage facilities can play an important role of providing energy balancing in electricity systems when the shares of intermittent photovoltaics and wind energy become significant. This study investigates a series of advanced Geographic Information System algorithms to locate prospective sites for pumped hydro, with a focus on short-term off-river pumped hydro energy storage which has little environmental impacts.

Mathematical models developed in this study represent two typical types of off-river pumped hydro reservoir sites: dry-gully and turkey’s nest, which have different characteristics as described in Section 3. The Geographic Information System algorithms first highlight the promising regions for pumped hydro developments with a variety of search criteria (Table 2), which significantly reduce the searching scope ensuring computational manageability (Fig. 8). Protected areas and intensive land uses are excluded in site searches to avoid any possible conflicts or competition with nature reserves, urban regions or intensive farming

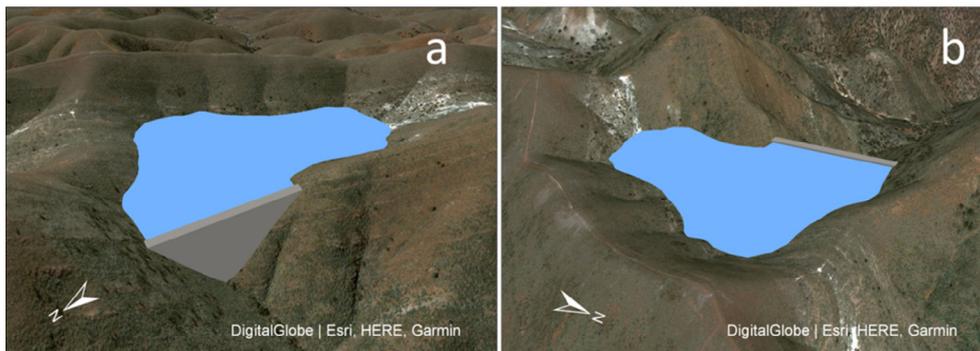


Fig. 10. 3-dimensional visualisation (a. frontview and b. backview) of a typical dry-gully site (elevation exaggeration: 2).

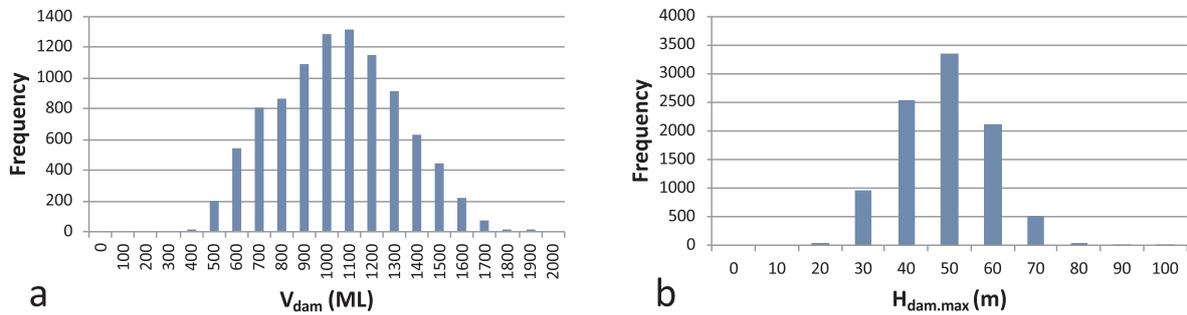


Fig. 12. Distributions of the excavation for dam construction (V_{dam}) and the maximum dam wall height ($H_{dam,max}$) within the promising regions (head > 300 m) of South Australia.

activities. Mapping of promising regions for pumped hydro developments as demonstrated in Figs. 6 and 7, can be used for the planning of renewable energy development zones such as [58].

The automatic Geographic Information System-based procedures work efficiently in the identifications of dry-gully and turkey’s nest sites and also yield a range of site information such as coordinates, elevation, water surface area, storage capacity, dam length and volume (Fig. 9). Prospective sites with higher water to rock ratios are further selected from a large number of identified overlapping sites, which can be then visualised in 3 dimensions (Fig. 10). Presentation of such site information facilitates the decision makings of local administrative authorities and project developers.

A case study is conducted for South Australia, which has high levels of photovoltaics and wind integration and the intermittency of renewable energy has already brought significant challenges to the electricity system economics and security. Despite having no existing hydro developments, South Australia demonstrates a large energy storage potential: 190 sites, with 441 gigalitres of water storage equivalent to 276 gigawatt-hours of energy storage assuming a minimum head of 300 metres, an usable fraction of 85% and an efficiency of 90% - far beyond the South Australia’s share to support 100% renewable electricity in Australia [15]. Promising regions for pumped hydro developments in South Australia are located in the Flinders Ranges and the Mount Lofty region near the capital city, Adelaide (Figs. 6 and 7).

Given the input of modelling only includes the information that is usually publicly available such as digital elevation models and protected areas datasets, this model can also be applied to other regions outside South Australia. By using the models developed in this study, high-resolution assessments of pumped hydro energy storage potentials can be efficiently conducted in other states or territories of Australia and elsewhere around the world.

Future work will include the development of a costing model. Cost-related information will be incorporated in the model which is now under development by experienced hydropower engineering consultants, including: (1) geology information such as rock types and structures which influence the stability and construction cost of dams; (2) geographical distances to existing high-voltage transmission network and transport infrastructure; (3) meteorology and hydrology conditions to determine the requirements for micro-catchments and evaporation reduction measures.

List of acronyms and abbreviations

CAPAD	Collaborative Australian Protected Area Database
CLUM	Catchment Scale Land Use
DEM	Digital elevation model(s)
DG	Dry-gully
GCS	Geographic Coordinate System

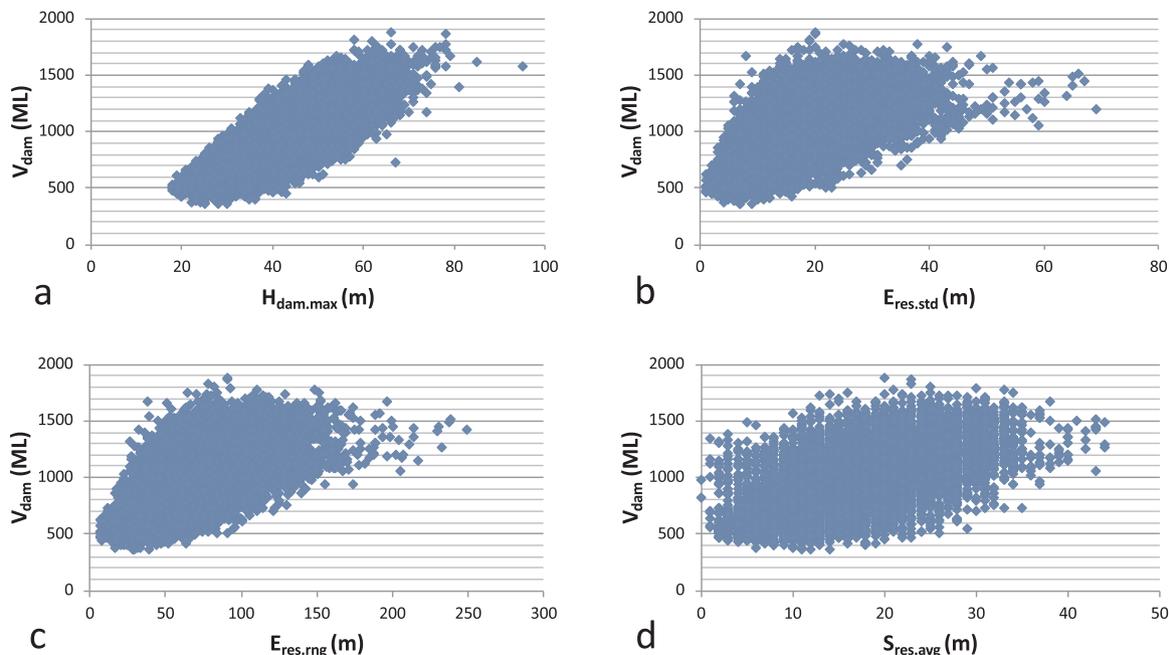


Fig. 13. Relationships between the excavation for dam construction (V_{dam}), the maximum dam wall height ($H_{dam,max}$), the standard deviation ($E_{res,std}$) and range ($E_{res,rng}$) of elevation and the average slope ($S_{res,avg}$).

GDA	Geocentric Datum of Australia
GIS	Geographic Information System
GL	Gigalitre(s)
GW	Gigawatt(s)
GWh	Gigawatt-hour(s)
H/D	Head to distance
HVDC	High-voltage direct current
kV	Kilovolt(s)
kW	Kilowatt(s)
kWh	Kilowatt-hour(s)
MW	Megawatt(s)
MWh	Megawatt-hour(s)
NEM	National Electricity Market
PHES	Pumped hydro energy storage
PV	Photovoltaics
SA	South Australia
STORES	Short-term off-river pumped hydro energy storage
TN	Turkey's nest
WGS	World Geodetic System
W/R	Water to rock

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Appendix A

Dam volume calculation incorporating freeboard and dam crest width is included in: <https://www.dropbox.com/s/vagey2kijogofet/Appendix%20B.docx?dl=0>.

Appendix B

A full collection of the identified dry-gully and turkey's nest sites is included in:

<https://www.dropbox.com/s/d53us0k78t4kf8r/DGSites168.xlsx?dl=0>

<https://www.dropbox.com/s/2t1pc2fpk65xcpd/TNSites22.xlsx?dl=0>

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