Geographic information system (GIS) algorithms to locate prospective sites for short-term off-river pumped hydro energy storage

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Abstract

Pumped hydro energy storage (PHES) is capable of large-scale energy balancing and providing a wide range of grid stabilisation services in a modern electricity system with high renewable energy penetration. Increasing interest in utilising closed-loop off-stream PHES to support high levels of intermittent renewable energy demands improved geographic information system (GIS)-based algorithms to identify prospective sites over a large land area. This study establishes mathematical models for two typical PHES locations, dry-gully and turkey's nest, and develops a sequence of automatic GIS-based procedures to locate sites for short-term off-river pumped hydro energy storage. By applying the site searching algorithms and a variety of search criteria defined in the modelling, a case study is conducted for South Australia, where 168 dry-gully sites and 22 turkey's nest sites are identified with a total storage capacity of 441 GL, 276 GWh. Sensitivity of the total storage capacity and the number of sites to two critical criteria is also explored. Dry-gully and turkey's nest site models developed in this study are also applicable to other types of PHES such as those adjacent to existing water bodies, old mining pits and ocean-based PHES.

Keywords: Geographic information system, energy storage, pumped hydro

1. Background

Photovoltaics (PV) and wind constitute approximately half of the global new generation capacity installed in 2014-16 [1, 2] and compose the vast majority of new-build power plants in Australia [3]. By the end of 2016, Australia's renewable energy integration exceeded 17% of total electricity generation [4]. South Australia has the highest penetration of non-hydro renewable energy in the states and territories of Australia, with approximately 48% of the state's annual electricity production coming from the variable renewable energy (VRE) sources photovoltaics (PV) and wind in 2016 [4]. This high VRE integration level is comparable to Denmark (> 50%) and Portugal (> 30%), which rank the top two countries of renewable energy penetration around the world excluding hydroelectricity [5]. However, unlike Denmark and Portugal where large-scale grid interconnection or hydro resources can help to support VRE integration, SA has a low level of interconnection with the rest of Australian National Electricity Market (NEM) via two interconnectors: Heywood (650 MW) and Murraylink (220 MW DC) and there is no significant hydro resource that can be exploited 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. For instance in July 2016, when a period of upgrading the Heywood interconnector coincided with low wind generation at peak times and high natural gas prices, the average wholesale electricity prices in SA surged to $229/MWh with 3 extreme price events on 7, 13 and 14 July beyond $5000/MWh [6]. The long-term average price in SA when the interconnector is in operation importing 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 [7, 8]. This included a state-wide blackout on 28 September 2016, when three 275 kV backbone transmission lines were damaged by storm [9].

While the affordability, reliability and security of electricity supply under high VRE penetration involves a wide variety of issues as discussed in the Australian Chief Scientist's final report on the review of the electricity market's security [10], the enhancement of grid interconnection and the integration of grid-scale energy storage are commonly considered to be most effective approaches, especially power systems that are weakly connected to other systems [11]. South Australian transmission network service provider, ElectraNet, has initialised a regulatory investment test for additional interconnections with neighbouring states Victoria, New South Wales (NSW) and Queensland, where 4 routes of new transmission links are being investigated, including 1100-1600 km of distance to NSW (Mt Piper) and Queensland (Bulli Creek) [12]. Australia's largest virtual power plant, which connects 1000 residential and commercial across Adelaide through a cloud-based platform, began operation in March 2017 [13]. Grid-scale lithium ion batteries with a power and energy capacity of 100 MW and 129 MWh respectively will be installed to balance intermittent energy production from the Hornsdale wind farm and to enhance grid stability in SA [14].

Deployment of pumped hydro energy storage (PHES), which constitutes 97% of the total capacity in world's energy storage markets, is also studied in SA. Opportunities for seawater PHES that utilises ocean as lower reservoirs are explored in the coastal regions of SA [15]. A proposed 100 MW project with 6-8 hours of storage, which is located at the top of the Spencer Gulf near Port Augusta and Whyalla, is under a feasibility study [16]. Recent studies [17, 18] from the Australian National University show Australia can build an affordable and secure electricity network with 100% renewable energy, using PV, wind, existing hydroelectric and biomass with the support of short-term off-river pumped hydro energy storage. Preliminary Geographic Information System (GIS)-based works [17, 19] suggest 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. Subsequent to the previous studies, this study focuses on developing a series of advanced GIS algorithms to identify prospective sites for short-term off-river PHES by screening over a large land area.

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 established in this study. Section 4 outlines the GIS algorithms used to identify 2 different types of PHES sites. Section 5 illustrates the results from site searching by applying the models and algorithms introduced in Section 3 and 4 to SA.

2. Literature review

2.1 PHES development

Developments of PHES began from 1890s and surged in 1960s, 70s and 80s in Europe, US and Japan where the rapid growth of nuclear energy and coal-fired units, which lack sufficient operational flexibility to accommodate changing demands, required the capability of load levelling. PHES was also regarded as an more economical alternative to oil and natural gas-fired plants for peak shaving, especially during the (post-) periods of energy crisis in 1970s [20, 21]. In some regions, PHES is operated for energy arbitrage, which profits from the differences of electricity price during the peak and off-peak periods, and also facilitates transmission congestion relief.

In recent years, the prosperity of variable renewable energy such as PV and wind has led to a resurgence of interest in PHES because of its outstanding capabilities of energy time-shifting and ancillary services such as frequency regulation and voltage support, which are critical to large-scale renewable energy integration. By the end of 2016, there are over 160 GW of PHES in operation around the world, amongst which more than 85% of the installations deployed in Europe (> 50 GW), China (32 GW), Japan (26 GW) and US (23 GW) [22]. Open-loop PHES, which is continuously connected to a naturally flowing water feature by the definition of the U.S. Federal Energy Regulatory Commission [23], dominates the deployment of existing PHES. Australia has 3 large PHES facilities (2.5 GW) operated in the NEM, Tumut-3, Shoalhaven, Wivenhoe, which are all incorporated in water supply and hydroelectric power generation schemes [22].

PHES is a mature technology of large-scale energy storage. Recent studies on PHES focus on:

- Its significant roles as large-scale energy storage to facilitate large VRE integration while maintaining system reliability and security [24-26]. The NEM and Western Australian studies [17, 18] also demonstrated that affordability can be maintained by PV, wind, PHES and high-voltage DC/AC transmission (HVDC/AC).
- Operation strategies to maximise profits from energy arbitrage in competitive electricity markets and providing inertial response and ancillary services such as frequency control [27-29].
- 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 [30-33].
- Seawater and underground PHES which has minimum environmental impacts to ecology systems [34-38].
- Modern adjustable-speed PHES with wide operating ranges and higher efficiency, as well as improved dynamic stability under grid disturbances [39].
- GIS-based siting to locate sites by utilising contemporary advanced GIS and remote sensing technology.

2.2 GIS-based siting

Developments of advanced GIS and remote sensing techniques in recent years allow acceleration of the planning and improvement of assessment accuracy such as automated site selection and evaluation at early stages of developing hydroelectric and water supply schemes. 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 to dozens of megawatts, including both run-of-the-river and storage types of hydroelectric. Larentis et al. 2010 [40] developed a computerised "Survey & Selection" methodology for the evaluation of small run-of-the-river and storage hydroelectric 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. 2010 [41] conducted a GIS-based site location with hydrological analyses for small run-of-the-river hydroelectric in northeast India, by searching from the outlet of watershed upstream to the fifth order of streams at an interval of 500 m. Yi et al. 2010 [42] undertook a cell-by-cell analysis to identify potential small hydro sites along the rivers and a scoring system was established in the modelling, incorporating a variety of issues including topography, hydrology and environmental impacts.

Automation of site searching for large-scale water supply projects is also explored. Petheram et al. 2017 [43] examined the opportunities for developing water supply schemes with a minimum catchment area of 10 km^2 in northern Australia. Calculations of dam development and reservoir inundation were conducted on each individual cell (pixel) of the streams within the region while the storage-cost and yield-cost (GL per $m) ratios were used to decide optimal dam locations and sizes.

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 2014 [44] investigated the potentials of utilising existing waterbodies in close proximity to hydroelectric or water supply schemes to serve as open-loop, pump-up PHES reservoirs on the basis of 4 critical criteria (capacity, area, distance, elevation difference) derived from the characteristics of 43 existing PHES in the contiguous U.S.. Gimeno-Gutierrez & Lacal-Arantegui 2015 [45] 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 TWh, especially in Turkey, Spain and the Alps countries. Jimenez Capilla et al. 2016 [46] demonstrated a multi-criteria GIS-based analysis of site selection for an existing dam to be retrofitted into PHES systems, which incorporates the aspects of topography, land use, geology and meteorology by applying the analytic hierarchy process into a decision model. Fitzgerald et al. 2012 [47] investigated the adjacent 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 GL, where the sensitivity of number of sites, energy storage capacity (GWh) and head to buffer distance (radius) was also studied. Similarly, Kucukali 2014 [48] 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 2017 [49] 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 at a large scale. Rogeau et al. 2017 [50] investigated the opportunities for small-scale PHES in France (with a minimum storage capacity of 500 kW x 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. 2010 [51] 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.

Increasing interest in closed-loop off-stream PHES [23] demands improved GIS-based algorithms to identify sites for various types of PHES as defined in, which can help relaxation of the constraints of developing PHES to support increasingly high integration of VRE.

2.3 Innovation

In this study, a series of GIS-based algorithms are developed for identifying prospective sites for the deployment of off-river PHES, which is capable of gigawatt hours-scale energy storage to support renewable energy integration and grid stabilisation. The innovation of this work includes,

- Establishment of dry-gully (DG) & turkey's nest (TN) site models for 2 typical types of suitable PHES sites, which incorporates the characteristics of large-head (> 300 m), medium-sized (10-100 ha) closed-loop off-river PHES.
- Development of a sequence of GIS procedures for quick screening for DG & TN sites over a large land area. This includes the computerised analyses of topography, land use and hydrology in GIS platforms, as well as the optimisation of site selection in the modelling.
- Application of a variety of search criteria, allowing the search scope reduces from millions to thousands of square kilometres and hence significantly accelerating the computationally-intensive site searching.

- Development of a collection of short-term off-river PHES sites in South Australia to help decision making of the state's energy sectors in promotion of reliability and energy security during the state's transition to 50-100% renewable electricity.

While this study focus on fresh-water off-river PHES located outside national parks and intensive land uses, the DG and TN site models developed in the modelling are also applicable for other types of PHES such as for identification of suitable DG or TN sites to locate upper reservoirs within a certain distance (buffer) from existing water bodies, old mining pits and ocean.

3. Models for potential PHES sites

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 $/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 component, 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 $/kWh.

For an off-river PHES plant, building a dam is a key issue of the project which also dominates the cost of storage components. This is because the issues related with the construction of conventional on-river hydroelectric such as flood control, immigration and environmental impacts are usually little or negligible for off-river PHES.

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 and hence the cost. In this study, 2 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 sites and turkey's nest sites. The definition of DG and TN sites is in line with the T2, T3 types of PHES in the European studies [52]. The TN and DG models outlined as follows were established 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 terrains 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}, A_{res} represent the volume and the surface area of a reservoir while V_{dam}, B_{dam} and $H_{dam.max}$ denote the earthwork required to build a dam and the dam's batter ratio and max wall height.

Dam batters of typical earth dams in USACE 2004 [53] 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 2005 [54] suggests 1:2.5 to 1:3.5 (upstream), 1:2 to 1:3 (downstream) for earth dams and 1:1.4 to 1:1.7 for rock-fill dams. 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 of DG and TN sites over 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 at a 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 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

$$V_{res} = V_{org} + \frac{V_{dam}}{2} \quad (1)$$

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

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

$$E_{dam} - E_i \geq 0, E_{dam} - E_j \geq 0 \quad (4)$$

$$H_{dam.max} = E_{dam} - E_{j.min} \quad (5)$$

Equations 1 to 5 demonstrate the calculations of V_{res}, $H_{dam.max}$, where L_{dam} represents the dam's crest length; V_{org} is the volume of the space impounded by existing terrain (without excavation) of the site and a dam without its thickness factored in; E_i, E_j and E_{dam} represent the elevations of the i cell of a reservoir, the j cell of a dam and the dam crest while the numbers of raster cells within the reservoir and the dam are m, n respectively. Eq. 1 assumes the excavation of soil or rock required to build a dam is from the area it encloses, which is subject to variation if external materials are needed such as for a concrete dam.

3.4 Other types of PHES sites

Due to 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 PHES in northern Queensland [55]. Opportunities for retrofit of existing hydroelectric also exist (though it is limited) such as the Snowy Hydro expansion scheme and in Tasmania, an island state with over 90% of electricity from hydro resources [56, 57]. Furthermore, a seawater PHES facility is being studied which is located at the top of Spencer Gulf of SA [16] though there are a number of challenges in the development of ocean-based PHES [19]. 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 of mining pits, hydroelectric and other existing reservoirs, as well as ocean.

4. GIS algorithms

A software named STORES is developed in the modelling which includes the following functional modules:

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

- 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 required undulating terrains. 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 [48-50, 58]. 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.

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 Digital Elevation Models. A threshold of minimum 111 accumulation cells is set in the delineation of virtual streams allowing the surface area of reservoir is greater than 10 ha at a resolution of approximately 30 m. Lu & Wang 2017 [49] 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 2017 [49], this study calculates the storage capacity of dry gullies and the required earthwork to build a dam through a watershed model (Fig. 3).

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. 3). This is used for a calculation of its own watershed for each pour point from its location and a flow direction raster derived from the DEM.

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 at a slope greater than 1:5 are not included in the calculation to exclude steep terrains which are more difficult to impound a reservoir with sufficient storage capacity. Moreover, it can avoid dam construction on a steep terrain though it may be technically feasible under some conditions [53].

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 [40] and [43]. 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. 3.

4.3 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 max dam wall height is 40 m, especially for the sites located on a virtual stream that flows across a gentle gully. 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 water-rock ratio is used to decide optimal sites with larger capacity while less earthwork when overlaps occur. The water-rock 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 water to rock 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 are integrated in future study.

4.4 Identifying Turkey's nest sites

While the GIS algorithms outlined in Section 4.2 and 4.3 are capable of a quick identification of DG sites as shown in Section 5.3, a different approach is needed to identify another type of PHES site, turkey's nest, as defined in Section 3.2. This is because the different characteristics of TN sites decide,

- TN sites are not necessarily located on a virtual stream network which is derived from DEM on the basis of number of accumulation cells greater than a certain threshold.
- Even being located on the stream network, a TN site usually incorporates its surrounding flat areas rather than only including its own watershed in order to increase the storage capacity while reducing dam walk heights.
- For lower reservoirs located at the bottom of hills, a TN site is usually preferred to facilitate the construction of underground powerhouse which accommodates most of machinery equipment.

Generally, a flatland or a natural depression is preferred for the dam construction at TN sites as local terrain characteristics decide maximum dam wall height and the required earthwork to build a dam. On a flatland (slope=0) for example in Fig. 4, a dam height of 15 m with an impoundment area of 5 hectares is capable of storing 1 GL of water while $H_{dam.max}$ and V_{dam} reduce to 13 m on a "depression"-like terrain with an average slope of 15%. In contrast, a "slope"- or "rise"-like topography with an average slope of 15% requires much larger $H_{dam.max}$ (17-25 m) and more V_{dam} (635-650 ML) to store 1 GL of water.

As described in Fig. 4, the max 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 ruler to reflect the appropriateness of terrains to build TN dams. Connolly et al. 2010 [51] developed a similar approach calculating maximum allowable earthworks to reflect the flatness of terrains while in this study, V_{dam} and $H_{dam.max}$ are used to assess the suitability for a TN dam 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 cellsize of the $H_{dam.max}$ raster is 360 m x 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.

A collection of the search criteria used in the modelling are listed in Table 2.

5. Case study

5.1 Input datasets

1 arc-second DEMs for South Australia are downloaded from the U.S. Geological Survey Long Term Archive. Given the surface area of a short-term off-rive PHES facility ranges from 10-100 ha, the resolution of DEM (approx. 30 m) is well suited, where a typical reservoir contains 100-1000 raster cells. The Collaborative Australian Protected Areas Database (CAPAD) and the Catchment Scale Land Use (CLUM) datasets, obtained 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 is 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.

5.2 Promising regions

South Australia has a land area of 983,482 square kilometres [59]. 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 over SA. Fig. 5 and Fig. 6 demonstrate two promising regions of SA highlighted from the modelling constituting 0.1% land 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 sufficient head to horizontal distance ratio greater than the threshold defined in Table 2. A minimum head to horizontal distance 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 share of SA to support a 100% renewable electricity grid in Australia, which is from the grid integration study [17].

As shown in the figures, the CAPAD areas and the intensive land use classes defined in the CLUM have been excluded to ensure the sites are outside national parks and without competition with such as urban areas. It is noted that despite fresh-water, large-head PHES is recommended in this study as discussed in Section 1, the potential seawater PHES sites can be identified from the modelling as well, such as the project now under development by EnergyAustralia located at west of the upper Spencer Gulf.

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. 7, the searching scope within South Australia reduces from nearly 1 million to 31 square kilometres after applying a sequence of GIS-based procedures including the exclusion of remote regions, CAPAD, CLUM Class 5 and slopes > 1:5. Eventually, 423 DG sites, which satisfy the criteria listed in Table 2, are identified from the searching algorithms and 168 out of them are included in the final set by comparing the water-rock ratios of overlapping reservoirs. Dots shown in the insets of the Fig. 5 and Fig. 6 represent the exact locations of DG sites included in the final set within some regions.

A snapshot of detailed information such as storage capacity and dam length is shown in Fig. 8, while a full collection of identified DG sites is included in Appendix. A promising DG site located at the coordinates -32.116638, 137.987237 is shown in Fig. 9 by 3D visualisation of the dam and reservoir in ArcGIS Pro.

The sensitivity of total storage capacity and number of sites to the max dam wall height is examined by varying it from 10 m to 80 m as illustrated in Fig. 10. Dams of the Snowy Mountains Schemes in Australia range from 18.3-116.5 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 [60].

5.4 Identified turkey's sites

As stated in Section 4.4, 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. 11 illustrates the distributions of Hdam.max, Vdam within the promising regions (head > 300 m) and Fig. 12 shows their relationships with standard deviation $E_{res.std}$ and range of elevation $E_{res.rng}$ as well as 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. 11, 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.

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

6. Conclusion and future work

This study demonstrates a series of GIS algorithms developed in the modelling are capable of a quick screening for short-term off-river PHES sites to be conducted over a large land area. Algorithms for highlighting promising regions with multiple potential heads allow exclusion of the regions without a sufficient head to horizontal distance ratio and hence reduces the searching scope from nearly 1 million to about 1000 square kilometres. Protected areas and intensive land uses are not included in the site searching avoiding any possible conflicts with such as national parks, or competition with urban and intensive farming activities.

The models for dry-gully and turkey's nest sites incorporate different characteristics of two typical types of off-river PHES sites, which can be used for estimates of gross off-river PHES potentials within a region at early stages of development. In addition, the modelling yields a range of useful information for the identified sites such as coordinates, elevation, water surface and ground areas, storage capacity, dam crest length and volume. The water-to-rock ratio applied in the study facilities the selection of most promising sites out of a large number of locations identified from high-resolution (10 m) site searching.

A case study for South Australia demonstrates a large storage capacity within the state, located in the Flinders Ranges and the Mount Lofty region near Adelaide. In total, 190 sites are identified with a gross storage capacity of 441 GL, which is equivalent to 276 GWh by assuming a minimum head of

300 m, a usable fraction of 85% and an efficiency of 90%. According to the need for large-scale energy storage in the NEM and the population size (demand) of SA, this storage capacity is far beyond the SA's share to support a 100% renewable electricity system in Australia. Given the integration of PV and wind in SA has already exceeded 45%, this analysis can make contributions to the decision making of local energy sectors regarding the new deployment of renewable energy. PHES can play a critical role in the state's pathways towards 50-100% renewable electricity since it is capable of mass energy balancing and a range of ancillary services such as frequency control to help maintain the system reliability and energy security.

While this paper only focuses on the development of an automated searching process for the dry-gully and turkey's sites of fresh-water PHES, the algorithms are also applicable for other types of PHES, such as for identification of suitable DG or TN sites to locate upper reservoirs within a certain distance (buffer) from existing water bodies, old mining pits and ocean.

Future work mainly includes,

- Development of a costing model. Cost-related information will be incorporated into cost functions/models which is under development by experienced hydroelectric engineering companies at next stage of the study. This consists of: 1) Geology such as rock types and structures that can determine the stability and cost of a dam; 2) Distance to high-voltage transmission lines (> 220 kV); 3) Meteorology and hydrology data to decide the requirements for rainfall collection facilities (a micro-catchment for example) and evaporation reduction measures such as floating covers.
- Environmental impact assessment (EIA). According to Wänn, A., et al. 2012 [61], EIA includes a wide variety of assessments of environmental impacts on ecology and natural systems, physical environment such as soils and hydrogeology, and human interaction from the activities of hydroelectric development. While off-river PHES has little environmental impacts because of: 1) no interaction with ecology of existing river systems, 2) being located outside protected areas and intensive land uses and 3) medium-sized dams and reservoirs, a throughout EIA will still be needed for any specific sites in the feasibility study.

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Appendix

A full collection of identified dry-gully and turkey's nest sites is included in Dropbox:
https://www.dropbox.com/s/d53us0k78t4kf8r/DGSites168.xlsx?dl=0
https://www.dropbox.com/s/2t1pc2fpk65xcpd/TNSites22.xlsx?dl=0

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