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Stream-Reach Identification for New Run-of-River Hydropower Development through a Merit Matrix–Based Geospatial Algorithm

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Abstract: Even after a century of development, the total hydropower potential from undeveloped rivers is still considered to be abundant in the United States. However, unlike evaluating hydropower potential at existing hydropower plants or nonpowered dams, locating a feasible new hydropower plant involves many unknowns; hence, the total undeveloped potential is harder to quantify. In light of the rapid development of multiple national geospatial data sets for topography, hydrology, and environmental characteristics, a merit matrix–based geospatial algorithm is proposed to identify possible hydropower stream reaches for future development. These hydropower stream reaches—sections of natural streams with suitable head, flow, and slope for possible future development—are identified and compared by using three different scenarios. A case study was conducted in the Alabama-Coosa-Tallapoosa and Apalachicola-Chattahoochee-Flint hydrologic subregions. It was found that a merit matrix–based algorithm, which is based on the product of hydraulic head, annual mean flow, and average channel slope, can effectively identify stream reaches with high power density and small surface inundation. These identified stream reaches can then be evaluated for their potential environmental impact, land development cost, and other competing water usage in detailed feasibility studies. Given that the selected data sets are available nationally (at least within the conterminous U.S.), the proposed methodology will have wide applicability across the country. **DOI: 10.1061/(ASCE)WR.1943-5452.0000429.** *© 2014 American Society of Civil Engineers.*

Author keywords: Hydropower resource assessment; New hydropower development; Stream-reach selection; Flood elevation.

Introduction

Hydropower, electricity generated from the kinetic and potential energy of streamflow, is the most widely used renewable energy in the world. The United States has used this clean, renewable energy source since the late 19th century, and it now has 78 GW of conventional hydropower and 22 GW of pumped-storage hydropower from 2,400 hydropower dams—producing 7% of the energy used in the United States annually [National Hydropower Asset Assessment Program (NHAAP) 2013]. However, even after a century of heavy hydropower development, a great amount of raw U.S. hydroelectric resource is still considered undeveloped (Hall et al. 2004). In recent decades, U.S. hydropower did not experience full growth, primarily because of heavier initial capital investment requirements (compared with other competing energy sources); unpredictable annual firm production caused by large interannual hydrologic variability, nonpower demands on water and storage that may be economically and environmentally more important than hydropower; and most important, potential environmental impacts on fishery resources and local riverine ecosystems (Kosnik 2008).

Although various studies on site-specific hydropower plant designs and operations provide solutions to the energy–environment problems (Fathi-Moghadam et al. 2013; Li et al. 2013; Kern et al. 2012; Wang and Liu 2012; Olivares and Lund 2012; Cheng et al. 2012; Goor et al. 2011; Yi et al. 2003; Barros et al. 2003), the research on hydropower resource assessment deserves more attention. Given the rising concern about fossil fuel carbon dioxide emissions (Kosnik 2008) and nuclear power security, renewable energy is becoming more important than ever. Hydropower is low cost, emission free, and responsive for grid stability and reliability (Ciocci et al. 2003). It is the primary source of renewable energy (producing approximately 63% of total renewable energy in the United States) and is expected to remain an important contributor to achieving a clean energy future. As a result, there is a strong need to study how to feasibly increase the national hydropower portfolio.

Different methodologies and data sets have been used to estimate the conventional hydropower resources available in the United States, from (1) expanding the capacity and improving the efficiency of existing hydropower plants; (2) retrofitting nonpowered dams (NPDs) for hydropower generation; (3) developing

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Note. This manuscript was submitted on June 2, 2013; approved on December 26, 2013; published online on December 28, 2013. Discussion period open until September 9, 2014; separate discussions must be submitted for individual papers. This paper is part of the ***Journal of Water Resources Planning and Management***, © ASCE, ISSN 0733-9496/04014016(11)/$25.00.

new (undeveloped) stream reaches; (4) discharging effluents; and (5) recovering available energy in constructed waterways. The National Hydroelectric Power Resources Study (NHS), led by the U.S. Army Corps of Engineers (USACE) Institute for Water Resources (USACE 1983) under the Water Resources Development Act of 1976, is perhaps the first comprehensive U.S. national hydropower resource assessment. The NHS team examined information for more than 50,000 existing dams and 10,000 undeveloped sites provided jointly by USACE dam safety personnel, state engineers, the Federal Energy Regulatory Commission (FERC), and the USGS. It was concluded that 46 GW of capacity and 124 terawatt hours (TW · h) of annual energy may be available from 1,948 candidate sites, of which 27 GW of capacity and 76 TW · h of annual energy were from 541 undeveloped sites (many of them yet to be developed). Although this was a nationwide hydropower resource assessment, the 10,000 undeveloped sites evaluated in the NHS had previously been studied and proposed by other entities. Therefore, there may be additional hydropower opportunities from new and unstudied streams; hence, the total undeveloped potential is not quantified.

Conner et al. (1998) performed a state-by-state hydropower resource evaluation for all potential sites documented in the FERC Hydropower Resource Assessment (HPRA) database, which primarily consists of FERC preliminary permit information. Some additional sites suggested by state agencies were also examined. In addition to the information provided by HPRA (e.g., head, streamflow, proposed capacity, and generation), Conner et al. (1998) developed a hydropower evaluation software that calculates a development suitability factor at each site. They concluded that 30 GW of capacity may be available from 5,677 sites across the United States, of which 8.5 GW was from 2,761 undeveloped sites. As with the NHS, the list of evaluated undeveloped sites was preidentified and most of them may not yet be developed.

Targeting for a comprehensive resource assessment covering all streams, Hall et al. (2004, 2006) performed a national-scale hydropower resource assessment using the USGS Elevation Derivatives for National Applications (EDNA) data set. EDNA is a hydrologically conditioned multilayer data set with synthetic rivers derived from the National Elevation Dataset (NED; Gesch et al. 2002). For each EDNA stream segment (average 3.2 km in length), the elevation drop was used as the hydraulic head to calculate the theoretical hydropower capacity, with annual streamflow estimated by regional regression formulae based on drainage area, precipitation, and temperature (Vogel et al. 1999). Hall et al. (2004, 2006) suggested that there may be 170 GW of hydropower capacity available from undeveloped sites across the United States. The work was recently extended in the Pacific Northwest Region by using a new impoundment development model (Hall et al. 2012).

Section 1834 of the Energy Policy Act of 2005 authorized multiple federal agencies within the U.S. Department of the Interior (DOI), DOE, and USACE to investigate hydropower development opportunities at federal facilities. These agencies examined 871 existing facilities to quantify the hydropower potential available at existing federal infrastructure (DOI et al. 2007). The observed maximum streamflow and head were used to calculate the maximum power that each site may provide. This study suggested that 1.2 GW may be available from NPD development and another 1.3 GW from capacity expansion at existing hydropower plants. Undeveloped sites were not examined in this study.

Following DOI et al. (2007), the U.S. Bureau of Reclamation (2011) conducted an in-depth study focusing on 530 Reclamation NPDs. Observed head and flow were collected to estimate the potential capacity, generation, cost-benefit ratio, turbine type, and other relevant information at each site. The 30% daily streamflow exceedance quantile was used as a standard for turbine selection. A total of 270 MW of capacity and 1.2 TW · h per year of energy were identified from 191 potential Reclamation NPDs.

Hadjerioua et al. (2012) conducted a national-scale NPD assessment for more than 54,000 NPDs documented in the USACE National Inventory of Dams (NID). The head and flow were estimated from NID attributes and the National Hydrography Dataset Plus (NHDPlus), respectively. A national total of 12 GW was identified, with over 90% of the capacity concentrated at the top 600 NPDs. Most of the NPD potential was predicted to be located at facilities in the USACE navigation lock and dam system. Powering these locks and dams may lessen concern regarding competing water uses and may potentially be initiated with less regulatory concern and stakeholder intervention.

Among the different possible hydropower sources, the hydropower potential from undeveloped stream reaches is considered to be the greatest, but also the hardest to quantify. Unlike evaluating hydropower potential at existing hydropower plants or NPDs, locating a feasible new hydropower plant involves many unknowns, which significantly increases the level of complexity. In addition, the lack of direct observation of head and flow challenges a more realistic assessment at the national scale. Fortunately, in light of the rapid development of multiple national geospatial data sets for topography, hydrology, and flood characteristics over the past decade, a new opportunity is arising for refining the calculation of hydropower resource potential from undeveloped stream reaches. An extremely large number of streams (more than 3 million stream segments, which can be defined as a portion of a stream that carries water from an upstream catchment to a downstream catchment documented in NHDPlus, with lengths varying from 0.8 to 80 km) can now be fully evaluated for possible hydropower development. The use of new data and site identification algorithms will also better capture the undeveloped national potential to support national strategic energy planning.

Given the pressing need, the primary purpose of this paper is to investigate how to objectively identify the location of undeveloped stream reaches for possible future hydropower development, particularly for new run-of-river projects with less surface inundation than traditional large storage projects. Hydropower stream reaches are defined as sections of natural streams with appropriate head, flow, and slope that may be suitable for development. A generalized geospatial assessment approach is designed to consistently estimate the hydropower potential across the country. Within each defined watershed, a merit matrix (i.e., an objective function that is a product of hydraulic head, annual mean flow, and average river slope) is suggested to establish the priority of each stream reach for new run-of-river development with minimal new surface inundation.

Although the consideration of complex and highly variable inundation and environmental relationship and the costs of land and alternative uses of water can make the model more realistic and ideal, this paper presents methodologies to accurately estimate the undeveloped hydropower potential based on hydrologic and hydraulic criteria. By thoroughly and consistently examining the entire river network, the total undeveloped potential can be accurately estimated and the stream reaches that may be worthy for further consideration can be identified. Thus, the model will narrow down the candidate stream reaches for complicated site-specific feasibility studies, including environmental impact assessment, engineering applicability, cost estimation, and water usage planning for market acceleration. The following sections describe the methodologies for geospatial data preparation, stream-reach identification, and power estimation, and offer a case study with comparisons among three different identification scenarios to demonstrate the applicability of this new approach.

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Methodology

The current practice of hydropower site selection is a combination of technical and financial analysis conducted by experienced developers and consultants. It involves many variables, including physical feasibility related to available head, flow, geological and topographical characteristics; energy factors related to potential capacity, potential energy, local electricity market, energy demand, and grid integration; and other related issues such as opportunity costs of hydro development that might include reduced water availability to meet nonpower demands and environmental impacts. Because of the high level of complexity (and the amount of baseline data that needs to be collected within the limited resource), the degree of effort required for a hydropower resource assessment is usually determined by the development timeline and need; a choice must be made between scale and accuracy.

Given that the primary interest of this paper is to develop a generalized geospatial assessment approach that may be applied consistently across the country, the effort will be targeted at the higher "reconnaissance level" (RETScreen International 2005). The major intent of this study is twofold: (1) develop the capability to build a relatively comparable estimate at the stream reach level so that "hot spots" for hydropower development can be revealed for further site-specific feasibility assessment; and (2) develop the capability to reasonably estimate the regionally aggregated total hydropower resource to support future energy planning needs. The methodology is designed for run-of-river projects because they result in less inundation than traditional large-storage reservoirs. The use of 100-year flood elevation as the maximum water surface elevation at the upstream of the project will ensure less inundation than the traditional large-storage reservoirs in this model. The methodology consists of the following three major steps: data set selection, geospatial processing, and stream-reach identification.

Data Set Selection

Multiple national-scale geospatial data sets are used in this assessment (Table 1). These data sets consist of geometric information on stream networks, hydrologic information on catchments, hydraulic information on river channels, boundaries of floodplains, elevations of ground and water surfaces, and locations of existing reservoirs, water bodies, and hydropower plants. Although the land cost information may also be useful, it is not considered in this study because such information is not always available in consistent data quality and may also vary frequently over time. Given that the selected data sets are available nationally (at least within the conterminous United States), the proposed methodology will have wide applicability across the country. Nevertheless, although the selected data sets may provide the highest spatial coverage and are considered accurate at the regional aggregated scale, they will not be sufficiently accurate to support direct site-specific engineering design. For a feasibility study at a potential site, direct measurements should be collected for reanalysis.

Geospatial Processing

Several geospatial processing steps are performed on the selected data sets.

Preliminary Screening

Among the 3 million raw NHDPlus (EPA and USGS 2010) flowlines in the conterminous United States [i.e., polylines with a unique NHDPlus COMID (common identifier of the NHD feature) identifier], approximately 90% are smaller river segments that have flow less than or equal to 1.7 m^3/s (60 ft^3/s). Given that it will require at least 71 m (230 ft) of head with 1.7 m^3/s of flow to generate 1 MW of hydropower (i.e., an unlikely situation for a run-of-river project), NHDPlus flowlines with estimated annual mean flow (Q_{NHDPlus}) of less than 1.7 m^3/s were excluded during the preliminary screening. This simplification is necessary for a national-scale assessment and is justifiable because the focus of this study is on run-of-river projects. If the focus becomes diversion projects with long penstocks, flowlines of less than 1.7 m^3/s can also be considered. Of the two available NHDPlus flow estimates, Q_{NHDPlus} computed by unit runoff approach was chosen in this study.

Assigning Stream Identifier

For computational needs, a unique identifier (Stream ID S) is assigned for each stream. Within a watershed of interest, the NHDPlus flowline with the largest Q_{NHDPlus} (i.e., outlet of the watershed) is identified and assigned $S = 1$ (Stream 1). Tracking up from this initial flowline, every connecting upstream flowline is also given the same Stream ID S. When a confluence point is encountered, the upstream flowline with the larger Q_{NHDPlus} is given the same Stream ID S, whereas the other flowlines (tributaries) with smaller flows are given $S + 1$ (and subsequently $S + 2, S + 3, \ldots,$ for all other contributing tributaries). When the upstream tracking of Stream S is completed, the process is continued on Stream $S + 1$ until all NHDPlus flowlines in the watersheds are labeled. During the labeling process, quality control is also performed to ensure that all NHDPlus flowlines are properly connected in a network of streams. It is also possible that there might be a solitary stream. This stream is given a new ID once all the streams in the network are identified. It is also necessary to check some geometric and hydraulic properties such as direction and slope of the flowlines. The flow direction may be opposite to the real direction because of errors when the data set was prepared. Sometimes flowlines are found with zero slopes, which may result as an error or because of rounding of the numbers, especially when the stream slope is

Table 1. Summary of Data Sets Used in this Study

Data type	Name of data set	Data source
Watershed boundary	Watershed boundary data set	U.S. Department of Agriculture Natural Resources Conservation Service
River geometry, existing water bodies, and flow estimates	National hydrography data set plus	U.S. EPA and USGS
Topography	National elevation data set	USGS
Floodplain boundary	Flood insurance study	US FEMA
Existing hydropower project characteristics	National hydropower asset assessment program data set	U.S. DOE/Oak Ridge National Laboratory

Note: Data from Gesch et al. (2002), FEMA (2012a), and EPA and USGS (2010).

very mild. This check is important because the assessment requires a positive slope in the stream network.

Flowline Discretization

The useful NHDPlus attributes, such as cumulative drainage area, elevation drop, and estimated flow, are provided with the flowlines. The flowline length can vary from less than 0.8 km to more than 80 km. Generally, most NHDPlus attributes refer to the downstream end of a flowline. For shorter flowlines, the attributes (e.g., flow) may reasonably be applied to the entire flowline, but such a simplification may not be suitable for much longer flowlines. It is possible that multiple NHDPlus flowlines may need to be identified to support a single hydropower plant, whereas in other cases, multiple hydropower plants may be colocated along a long NHDPlus flowline. Using the same attribute values for an entire stream segment can be misleading when identifying an appropriate location for a proposed plant in the stream segment, especially if the stream segment is very long. Therefore, it is necessary to discretize the stream networks at a finer spatial resolution for further assessment. After some trial and error, it is suggested that all NHDPlus flowlines be discretized into 150-m-long subsegments to better identify possible locations for hydropower development. The Q_{NHDPlus} is also linearly interpolated for each subsegment to reflect the gradual increase of flow along a flowline (although the increment is usually very small). When the discretization is completed, following the Stream ID from lowest to highest, a unique subsegment ID X is given from $1, 2, 3, \ldots,$ to each discretized subsegment. These subsegments will be used as the fundamental spatial units for assessment.

Calculation of Elevation and Head

Two kinds of height-related information are computed at the downstream for each subsegment X: channel elevation, Z, and maximum allowable hydraulic head, H.

For each subsegment X, channel elevation refers to the normal surface water elevation at the downstream end of a subsegment (Fig. 1). Because the primary objective of a hydropower resource assessment is to determine the possible net hydraulic head that may be available (i.e., approximate new pool elevation minus normal surface water elevation), channel elevation refers to a normal water surface instead of a river bed. The use of water surface elevation is also constrained by data, because the current digital elevation models can provide only water surface elevation instead of river bed elevation. Given that the channel elevation is already provided by NHDPlus at both the upstream and downstream ends of a flowline, linear interpolation is performed to estimate the channel elevation at each discretized subsegment (at the downstream of the subsegment), assuming no abrupt slope change in between.

To provide a consistent and independent reference for the evaluation of potential areas for new hydropower development across the nation, the FEMA Flood Insurance Study (FIS) flood elevation was used in this study (FEMA 2012a). Given the higher insurance rate and other regulatory considerations, there are usually fewer existing residences or civil structures in the current FEMA 100-year floodplains (FEMA 2012b, 2006). Therefore, if new hydropower development can be bounded by FEMA 100-year floodplains, it is hoped that there will be less inundation, resulting in a smaller amount of land acquisition (compared to the traditional large-storage reservoirs), and the likelihood of future development will be elevated. In other words, the current FEMA 100-year flood line can be regarded as an invisible boundary of existing civil development to guide this hydropower resource assessment. A reference height, H_{ref}, defined as the height from a discretized subsegment to the nearest FEMA 100-year flood line, is introduced in this study. The H_{ref} can be considered as the maximum allowable hydraulic head for new hydropower development, under the assumption that new hydropower development would not exceed the current 100-year FEMA floodplains.

To estimate H_{ref} for each discretized NHDPlus subsegment, a cross-sectional profile is drawn perpendicular to each subsegment at the downstream point. The end points of a cross-sectional profile are defined when the cross-sectional line touches the FEMA 100-year flood boundary. To be consistent with the simplification used in preliminary screening, a quality control procedure was performed to exclude FEMA flood boundaries corresponding to smaller streams (i.e., flowlines with Q_{NHDPlus} of less than $1.7\ \mathrm{m}^3/\mathrm{s}$). The elevation of these intersected points is referenced from the 10 m NED. Because the identified H_{ref} may be slightly different from either side of the river banks, an average value is used. If a certain section of FEMA flood line is missing, the 100-year flood elevation is interpolated from the upstream/downstream subsegments. Also, the elevations may occasionally be inconsistent among NHDPlus, various FEMA FISs, and 10 m NEDs, and this disagreement may generate bumps and spikes in the water surface elevation. To avoid these sudden bumps and spikes, H_{ref} calculated at several neighboring NHDPlus subsegments may need to be averaged for smoothing. An example is shown in Fig. 2.

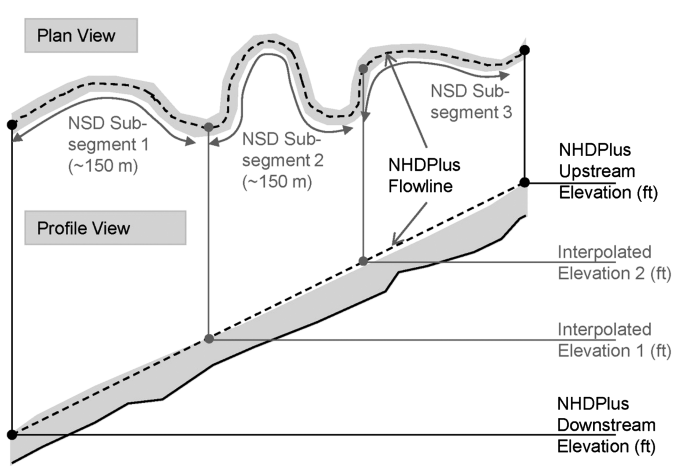

Fig. 1. Illustration of NHDPlus flowline discretization

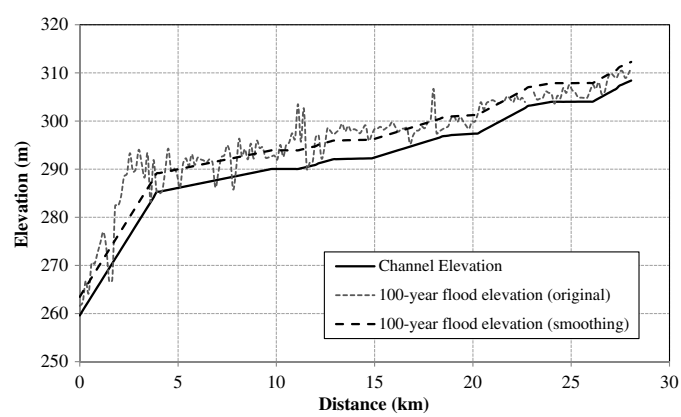

Fig. 2. Typical elevation profile with and without smoothing

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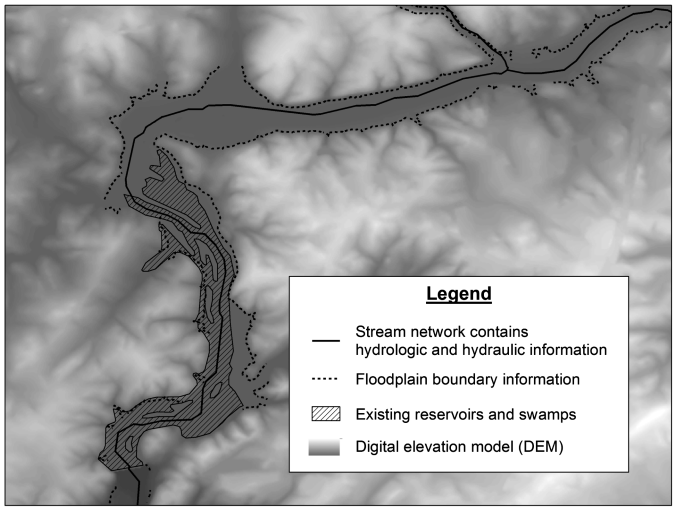

Fig. 3. Illustration of required data (data from EPA, USGS, and FEMA)

Labeling Water Bodies and Existing Hydropower Plants

Because the objective is to identify hydropower potential from "undammed" streams, subsegments overlapping with existing lakes/reservoirs are excluded from analysis; their hydropower potential is classified under the NPD category. The estimates of hydropower potential from existing NPDs involve different considerations and should be analyzed separately (Hadjerioua et al. 2012). To exclude existing lakes and reservoirs, the geospatial shape file of existing water bodies from NHDPlus was used. As long as a subsegment X is within 300 m of an existing water body, the subsegment X is labeled as "unavailable" for further assessment. Fig. 3 illustrates the required data sets for this study.

Stream-Reach Identification

After the geospatial processing is completed, a series of 150-m subsegments, X_i, with $i = 1, 2, \ldots, n$ are organized, in which n represents the total number of subsegments in the watershed of interest. For each X_i, S, geospatial coordinates, Q_{NHDPlus}, Z, H_{ref}, and all other original NHDPlus attributes (e.g., cumulative drainage area, COMID ID, and river name) are available in a tabulated form. An availability flag, F_i, is set for each subsegment, with $F_i = 1$ representing "available for hydropower development" and $F_i = 0$ indicating "unavailable for development" (i.e., subsegment overlapping with existing reservoirs and/or hydropower plants). In addition, places of stream confluence are marked. The pool of subsegments is used to identify the potential location for hydropower development. Under specified searching scenarios, a suitable set of neighboring subsegments for which the backwater effect is identified are grouped as a hydropower stream reach for hypothetical development. Three searching scenarios are tested and compared in this study.

Scenario 1: Equal Reservoir Length Approach

Scenario 1 is targeted to build a baseline estimate for comparison. Conceptually analogous to the previous studies, it is assumed that each stream reach is approximately 2 mi long (i.e., 3,300 m, composed of 22 consequent subsegments). The H_{ref} is not used in this baseline scenario. It includes the follow steps:

1. Starting from the most downstream and undeveloped subsegment X_i (i.e., the smallest i with $F_i = 1$), examine whether subsegments X_i to X_{i+21} are (1) located on the same stream (with the same S) and (2) available for development ($F_i = F_{i+1} =, \ldots, = F_{i+21} = 1$);
2. If the criteria in Step 1 are not satisfied, set F_i to 0. Return to Step 1 and continue the examination of X_{i+1};
3. If both criteria in Step 1 are satisfied, check whether there is any confluence among X_i to X_{i+21}. If stream S_j enters the current stream, use the elevation Z of X_{i+21} as a threshold to identify all subsegments X_j on stream S_j with elevations less than X_{i+21}. If any of the F_j values is 0 (i.e., developed on tributary), set F_i to 0, return to Step 1 and continue the examination of X_{i+1};
4. Following Step 3, merge X_i to X_{i+21} as a stream reach for hypothetical hydropower development and set F_i to F_{i+21} to 0. If there is confluence identified in Step 3, set F_j to 0 in addition;
5. Return to Step 1 and continue the examination of X_{i+22}, until all F values are 0; and
6. The end result should be a set of fixed length (3,300 m) stream reaches for further evaluation. The annual mean flow Q_{NHDPlus} of a stream reach refers to the flow at the most downstream subsegment. The H is estimated by the total channel elevation drop of a stream reach. Stream reaches for potential hydropower development do not overlap with existing water bodies and/or hydropower plants.

Scenario 2: Full Development Approach

Scenario 2 is targeted to maximize power, with the constraint that new development will not exceed the current 100-year floodplain. It places the first stream reach at the farthest point downstream (i.e., the location with the highest flow) and gradually searches upward until all undeveloped subsegments are searched for hypothetical hydropower development. In other words, it is a "bottom-up" hydropower development scenario, from the most downstream point up the entire river network. Unlike the reservoir length fixed in Scenario 1 (3,300 m), the reservoir length can be flexible in this scenario. It includes the follow steps:

1. Starting from the most downstream point and undeveloped subsegment X_i (i.e., smallest i with $F_i = 1$), calculate the maximum pool elevation, Z_{mp}, as the channel elevation Z plus H_{ref};
2. Along the same stream, examine all subsegments above X_i to identify consequent subsegments $X_{i+1}, X_{i+2}, \ldots, X_{i+m}$ with channel elevation Z of less than Z_{mp} and all subsegments available for development ($F_i = F_{i+1} =, \ldots, = F_{i+m} = 1$);
3. Check whether there is any confluence among X_i to X_{i+m}. If stream S_j enters the current stream, use the elevation of X_{i+m} as a threshold to identify all subsegments X_j on stream S_j with elevation of less than X_{i+m}. If any of the F_j values is 0 (i.e., developed), reduce $m = m - 1, m - 2, \ldots$, and update the set of X_j and S_j;
4. Merge X_i to X_{i+m} as a stream reach for hypothetical hydropower development and set F_i to F_{i+m} to 0;
5. Return to Step 1 and continue the examination of X_{i+m+1} until all F values are 0; and
6. The end result should be a set of stream reaches for further evaluation. The reservoir length, L, is calculated by $150 \times (m + 1)$. The Q_{NHDPlus} and H are defined similarly to Scenario 1 (i.e., equal reservoir length approach). None of the stream reaches overlaps with existing water bodies and/or hydropower plants.

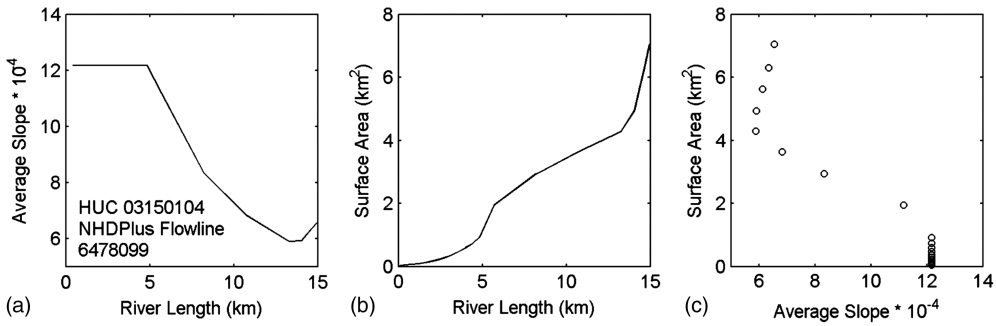

Fig. 4. Relationship between (a) river length and average channel slope; (b) river length and surface area; (c) average channel slope and surface area

Scenario 3: Merit Matrix–Based Approach

Although Scenario 2 can lead to the maximization of hydropower (i.e., the highest product of hydraulic head and flow), it does not consider topographical features. Scenario 2 gives strong preference to the most downstream stream reaches because of their higher power (because the relative contribution of flow is much higher than the relative contribution of head at the most downstream point of a stream network), whereas in reality those locations are less likely to be a priority owing to very flat topography. Scenario 2 also tends to generate extended stream reaches with large surface inundation, particularly for flat areas. Therefore, based on the desire to jointly maximize hydropower output and minimize inundation, a merit matrix–based approach is proposed in Scenario 3. A merit matrix, M, is defined by the product of H, Q_{NHDPlus}, and average channel, Sl:

$$M = H \times Q_{\mathrm{NHDPlus}} \times Sl \tag{1}$$

The objective is to search for stream reaches that may be worthy of development and may result in smaller inundation. In Eq. (1), the product of H and Q_{NHDPlus} is proportional to power and energy, so the larger value is more desirable. Although the process is targeted at minimizing inundation, it is fairly computationally expensive to estimate inundation (a function of topography and H) for all subsegments X for optimization. Hence, a simplification is made to maximize Sl instead, because higher Sl is usually associated with smaller inundation. An example is shown in Fig. 4, referenced to the downstream end of NHDPlus flowline 6499098. Fig. 4(a) shows the relationship between upstream river length (distance to the reference point) and average slope, calculated by elevation drop divided by river length. As expected, longer river length is associated with smoother average slope. The initial flat region is primarily caused by the limited spatial resolution of NHDPlus. Using 10 m resolution NED topography and assuming a hypothetical dam height to be the elevation drop, the potential inundation is delineated and shown in Fig. 4(b). Although the inundation increases with dam height and river length, the increase rate is not constant and is primarily controlled by topography. Fig. 4(c) shows the relationship between slope and surface area. This typical example indicates that the average slope is generally negatively correlated to inundation; hence, maximizing slope S will be similar to minimizing inundation. A conceptual illustration of Scenario 3, shown in Fig. 5, includes the following steps:

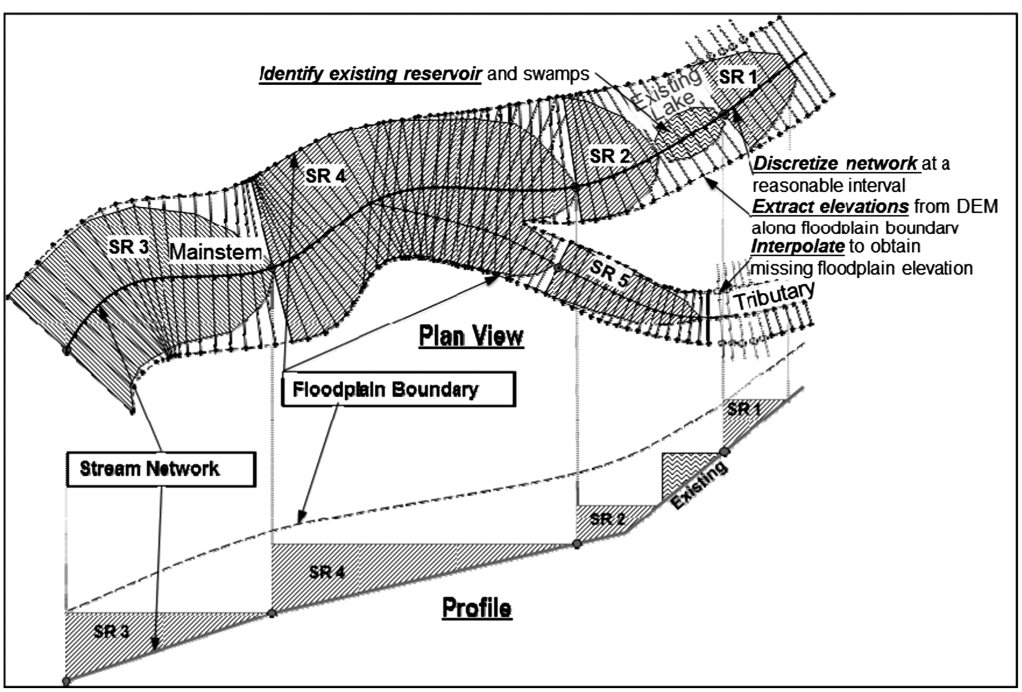

Fig. 5. Illustration of stream reach (SR) identification

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1. For each subsegment X_i with $F_i = 1$ (undeveloped), calculate the maximum pool elevation, Z_{mp}, as the channel elevation plus H_{ref};
2. Following Step 1, for each undeveloped subsegment $X_i(F_i = 1)$, examine all upstream subsegments above X_i to identify consequent subsegments $X_{i+1}, X_{i+2}, \ldots, X_{i+m}$ with channel elevation less than Z_{mp} and available for development $(F_i = F_{i+1} =, \ldots, = F_{i+m} = 1)$;
3. Following Step 2, for each undeveloped subsegment $X_i(F_i = 1)$, check whether there is any confluence among X_i to X_{i+m}. If stream S_j enters the current stream, use Z of X_{i+m} as a threshold to identify all subsegments X_j on stream S_j with elevation of less than X_{i+m}. If any of the F_j values is 0 (i.e., developed on tributary), reduce $m = m - 1, m - 2, \ldots,$ and update the set of X_j and S_j;
4. Following Step 3, for each undeveloped subsegment $X_i(F_i = 1)$, estimate H as the difference of channel elevation between X_{i+m} and X_i. The computed head will not exceed Z_{mp}. Calculate the reservoir length, L, as $150 \times (m + 1)$ and average slope Sl as H/L;
5. Following Step 4, for each undeveloped subsegment $X_i(F_i = 1)$, compute the merit matrix M_i. Identify the largest M_i and the corresponding $X_i, X_{i+1}, \ldots, X_{i+m}$. Merge X_i to X_{i+m} as a stream reach for hypothetical hydropower development and set F_i to F_{i+m} to 0;
6. Return to Step 1 and continue the calculation of merit matrix M_i in addition to the stream-reach identification until all F values are 0; and
7. The end result should be a set of stream reaches for further evaluation. None of the stream reaches should be overlapped with existing water bodies and/or hydropower plants.

The three scenarios result in a set of stream reaches for hypothetical hydropower development. However, many of the stream reaches may not be technically feasible (e.g., hydraulic head is too low). The theoretical hydropower P (MW) is computed by Eq. (2) for all stream reaches:

$$P = \eta \times \gamma \times H \times Q/10^6 \tag{2}$$

where $\eta = 0.85$ = assumed generating efficiency (also used in USACE 1983); $\gamma = 9{,}800\ \text{N/m}^3$ = specific weight of water; H (m) = hydraulic head calculated by the elevation drop of each stream reach; and Q (m^3/s) = hydraulic capacity estimated by Q_{NHDPlus}. To focus on valuable stream reaches, all stream reaches with P (power) of less than 0.95 MW are excluded in the following case study. In addition, given that the current hydropower technology can hardly harvest profitable energy from very low head conditions, all stream reaches with H of less than 1.5 m (5 ft) are also excluded.

Case Study

The proposed method was tested in two USGS hydrologic subregions (HUC4s), Alabama-Coosa-Tallapoosa (ACT) and Apalachicola-Chattahoochee-Flint (ACF) in the southeastern United States (Fig. 6). ACT (hydrologic unit code [HUC] 0315) and ACF (HUC 0313) are located in the South Atlantic–Gulf region (HUC 03). These two subregions cover an approximately 11,000 km long stream [i.e., total length of NHDPlus flowlines with Q_{NHDPlus} of more than 1.7 m^3/s (or 60 ft^3/s) within an area of 111,700 km^2]. Metropolitan areas within the subregions include Atlanta (Georgia), Albany (Georgia), Columbus (Georgia), Birmingham (Alabama), and Montgomery (Alabama). Annual precipitation for ACT–ACF ranges from 800 to 1,600 mm/year, with the most

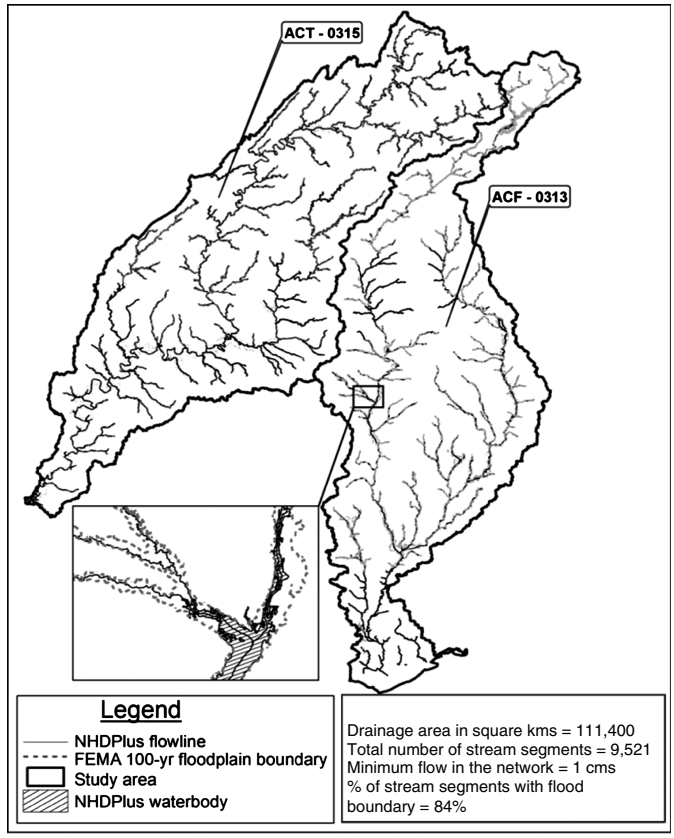

Fig. 6. Case study area (ACT–ACF subregions) (data from USDA Natural Resources Conservation Service, EPA, USGS, and FEMA)

precipitation falling in early spring and summer (from PRISM data set; Daly et al. 2002). The two subregions contain 32 hydropower dams and six major NPDs (Hadjerioua et al. 2012), with an aggregated storage capacity of more than 13 billion m^3. These facilities are primarily owned by USACE and Georgia Power Company [National Hydropower Asset Assessment Program (NHAAP) 2013].

Most geometric, hydraulic, and hydrologic information for the stream networks is included in NHDPlus. These attributes include cumulative drainage area, flow direction, flowline geometry, maximum/minimum channel elevation, slope, annual mean flow, and velocity estimates. NHDPlus flowlines with Q_{NHDPlus} of more than $1.7\text{m}^3/\text{s}$ are overlaid with FEMA 100-year floodplain boundaries during the initial quality control process. Of the 7,400 flowlines, FEMA 100-year floodplain information can be linked to approximately 6,200 flowlines (84%). Following the geospatial processing steps, the NHDPlus flowlines are labeled with Stream ID S and discretized into 150-m subsegments X. The channel elevation, Z, and reference height, H_{ref}, are estimated for all subsegments. The availability flag, F, is also set to indicate the subsegments overlapping with existing reservoirs and hydropower plants. Three scenarios are used to identify hydropower stream reaches for hypothetical development. The stream reaches with P of less than 0.95 MW or H of less than 1.5 m are omitted from further comparison.

Because the merit matrix is designed to minimize inundation, there is a need to directly estimate the possible inundation for further validation. This inundation area can also be used to check whether the area is constrained by the 100-year flood limit. Thus, a separate geospatial analysis is performed on these identified stream reaches. Assuming that a dam will be located at the downstream

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Table 2. Summary of Hydropower Stream-Reach Identification

Statistics	Scenario 1	Scenario 2	Scenario 3
Number of stream reaches	125 (2,570 before exclusion)	156	390
Average hydraulic head per reach (m)	6.9	9.5	6.1
Average hydraulic capacity per reach (m^3/s)	100	80	34
Total estimated power (MW)	380 (932 before exclusion)	751	628
Average estimated power per reach (MW)	3.0	4.8	1.6
Average reservoir length per reach (km)	3.3	15.7	7.1
Average slope per reach	0.00208	0.00191	0.00253
Average inundation area per reach (km^2)	2.4	12.9	2.8
Average reservoir storage per reach (10^6 m^3)	5.6	47.5	7.5
Average residence time per reach (day)	2.4	22.0	4.5

end of a stream reach with virtual dam height as H_{ref} and pool elevation as Z_{ref} (i.e., channel elevation plus H_{ref}), the possible area of inundation is delineated by using the 10 m–resolution NED. All NED grid points that are upstream of the virtual dam with elevation of less than Z_{ref} are identified as the possible inundated area. The total area, A (km^2), and the reservoir storage, V (m^3), are computed for each of the identified stream reaches. The geospatial functions required for this operation are available in standard geographical information system (GIS) software such as ESRI *ArcGIS*. Using Q_{NHDPlus} and V, the residence time T (day) can be estimated by

$$T = V/(Q_{\mathrm{NHDPlus}} \times 86{,}400) \tag{3}$$

Both storage and residence times are useful stream-reach characteristics for understanding how a hydropower plant may operate flexibly under natural hydrologic variability. For instance, if two stream reaches have the same storage capacity, the one with a shorter residence time (e.g., hours) will be easier to drain than the one with a higher residence time (e.g., days). Residence time may hint at the potential for a future power plant to provide ancillary services and flexibility to the electric grid. Residence time can also provide some relative indication of possible future water quality concerns.

The results in ACT–ACF are summarized in Table 2. For Scenario 1, because the reservoir length is fixed at 3,300 m (approximately 2 mi) and is much shorter than in the other two scenarios, the elevation drop is also found to be smaller. As a result, over 95% of the stream reaches identified through Scenario 1 are excluded because of the low-head constraint (i.e., hydraulic head less than 1.5 m). For the remaining 125 stream reaches, the total theoretical power is 380 MW, which is the lowest among the three scenarios (not surprising because most of the stream reaches are excluded as a result of low head constraint). Given the shorter, fixed reservoir length, the average reservoir storage and residence time are the lowest. Although it seems that Scenario 1 would result in the smallest surface inundation, it was overly simplified and significantly underestimated the power potential. Therefore, it may not be suitable for large-scale hydropower resource assessment.

For Scenario 2, the identified stream reaches are the longest (averaging 15.7 km per stream reach). As expected, this scenario

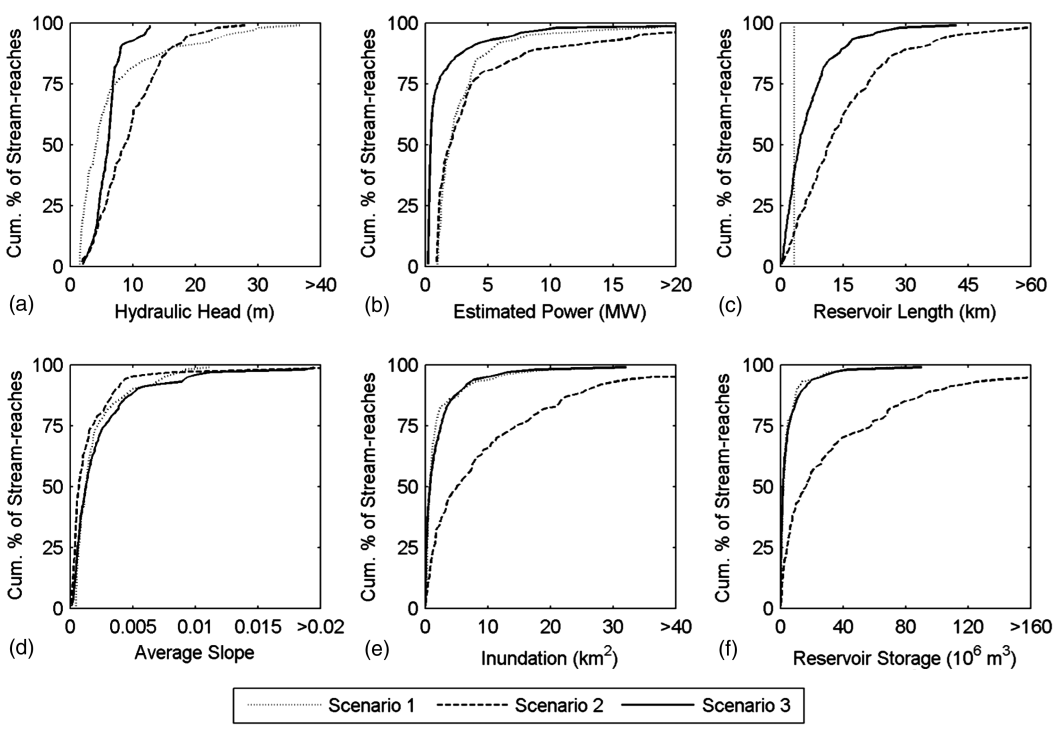

Fig. 7. Distribution of potential site characteristics from stream-reaches identified from three different scenarios: (a) hydraulic head; (b) estimated power; (c) reservoir length; (d) average slope; (e) inundation; (f) reservoir storage (the maximum may not be shown within the selected range of plotting)

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provides the highest theoretical power of the three scenarios (751 MW) because the stream reaches are generally found to be longer (indicating why the power potential is less in Scenario 1); but the trade-off is that it significantly increases the surface inundation (five times larger than in Scenarios 1 and 3). This results in the largest inundation and the longest residence time. The slope in Scenario 2 is the smoothest, which corresponds to the assumption that slope is negatively correlated to inundation.

For Scenario 3, the identified stream reaches are shorter (averaging 7.1 km per stream reach), resulting in a larger number of stream reaches (2.5 times more than in Scenario 2, with its longer stream reaches). Although the total power is smaller than in Scenario 2, total power is nonetheless higher than in Scenario 1 (628 MW, 84% of Scenario 2). Most important, the merit matrix performs as desired. The inundation, reservoir storage, and residence time are much lower than in Scenario 2, but only slightly higher than in Scenario 1. It does consider the trade-off between power generation and surface inundation.

Using the same set of data, the cumulative distributions of hydraulic head, estimated power, reservoir length, average slope, inundation, and reservoir storage are plotted in Fig. 7 for all scenarios. Scenario 2 tends to result in the highest hydraulic head [Fig. 7(a)] (given the maximizing nature of the longer reservoir length). For estimated power [Fig. 7(b)], Scenario 3 is the smallest. As a result of the equal reservoir length approach, the reservoir length of Scenario 1 [Fig. 7(c)] is a straight line. Scenario 2 identifies longer stream reaches than Scenario 3. Given that the average slope [Fig. 7(d)] is optimized in Scenario 3, the average slope is the steepest and results in a large difference between Scenarios 2 and 3 for inundation [Fig. 7(e)] and reservoir storage [Fig. 7(f)].

Comparing Scenarios 2 and 3, it is clear that Scenario 2 will lead to larger, longer hydropower stream reaches and Scenario 3 will lead to smaller, shorter ones. The residence times in both scenarios are small, and they can be considered as run-of-river projects (as opposed to the multiyear residence time for larger storage projects like Hoover Dam, Arizona–Nevada in the United States). Although in terms of total power, Scenario 2 is the largest, its much larger inundation may be more challenging for future development. Most important, because one major purpose of this study is to identify hot spots for future hydropower development, the results of the merit matrix–based approach (Scenario 3) will be more useful because it targets the identification of optimized locations for future developments.

The current merit matrix is not designed at the level of economic and site-specific feasibility analyses. Rather, the model is general in nature and can be applied to most watersheds, provided that the required hydrologic, hydraulic, topographic, and flood information are available. For highly regulated basins like ACT–ACF, the following site-specific analyses, including the environmental impact assessment and water usage analysis, may be even more challenging. For instance, the hydropower benefits in the ACT–ACF basins should be compared with the benefits of other water usage such as water supply, in-stream flow protection, and recreation (McMahon 2009; McMahon et al. 2004). To optimize the selection of stream reaches for consideration of more in-depth feasibility, the merit matrix will need to be further customized for different objectives. This will be explored in future studies.

Discussion and Conclusions

In this study, a generalized geospatial assessment approach is designed to estimate hydropower potential by using multiple state-of-the-art national geospatial data sets. A merit matrix–based geospatial approach is introduced, including several major steps: GIS processing, stream network discretization, and hydropower stream-reach identification. A case study is presented in two selected hydrologic subregions (ACT–ACF) for three different stream-reach identification scenarios. The results suggest that the proposed merit matrix approach (Scenario 3) can jointly maximize hydropower output and minimize inundation, and hence, can help to identify more suitable stream reaches for possible future hydropower development. Given that the driving data sets are available nationally (at least within the conterminous United States), the proposed methodology will have wide applicability across the country.

However, the proposed methodology is targeted at the higher reconnaissance level; hence, it does not produce estimates of capacity, production, cost, or impacts of sufficient accuracy to determine absolute economic feasibility or to justify financial investments in individual site development. It does, however, allow for the identification of hydropower stream reaches with high energy intensity. Although the total hydropower potential at a stream reach may be estimated quickly by assuming a simplified dam development model, the real world development can be very flexible by using a combination of penstocks and diversion structures. Also, considering environmental and other important aspects of development, the design hydraulic head may be very different from the H_{ref} (FEMA 100-year floodplain) used in this study. Therefore, although this study can point to a potential stream reach, that stream reach should not be interpreted as the exact suitable location for final development. The site-specific feasibility assessment cannot be overlooked.

Other important limitations include not considering the value of water for various usages. The benefit of hydropower generation versus that of other water usage such as in-stream flow protection, recreation, and water supply needs to be better evaluated. The costs of land and environmental impacts should also be considered in future studies. Nevertheless, following the framework developed in this study, the merit matrix can be adjusted to accommodate for different needs. Results from different merit matrices can be compared for more informed decision on the selection of stream reach for hydropower development under various constraints. In addition, although the selected data sets (e.g., NHDPlus and NED) are recognized as the best available geospatial data sources, they are still not comparable to the accuracy of direct observation; thus, the uncertainty should not be overlooked. The annual mean flow, Q_{NHDPlus}, is extremely useful in this study, given its wide availability for all streams, but the estimate is not always consistent with the corresponding USGS gauge observations. In addition, when designing a hydropower plant, the design flow threshold should be interpreted from an appropriate quantile on the flow duration curves (U.S. Bureau of Reclamation 2011). When considering how to incorporate the actual gauge observation, Q_{NHDPlus} may need to be further adjusted for a more suitable flow matrix. Such issues are beyond the scope of this initial study and will be pursued in the future.

Also, although the FEMA 100-year floodplain is used to estimate hydraulic head, this does not imply that FEMA floodplains will remain unchanged after a new hydro dam is placed. Whenever there is a new obstruction across a river, there is a potential for an increase in the flood elevations upstream; new FIS and floodplain delineation may be requirements of new hydropower development, depending on the details associated with any particular project's design and operation. Because a FEMA FIS is not always available (especially in rural areas), in some cases, an alternative height (similar to the FEMA 100-year floodplain) may need to be derived to estimate hydraulic head.

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This study implicitly assumed that the floodplain boundary obtained from FEMA will agree with NED, but in fact these two data sets have differing data accuracies. Typically, the FEMA floodplain data set is based on a hydrodynamic model with inputs from survey data at finer spatial resolution, whereas the resolution of NED is generally coarser. Therefore, it is likely that these two data sets may not agree with each other, especially along a narrow valley or steep river bank. Elevations obtained from NED along the floodplain boundary should be further smoothened and quality controlled. Because of scale issues, it is possible that at some locations, the downstream water surface elevation may be higher than the upstream elevation. The data concern should be addressed during the quality control stage.

Finally, this study basically assumes that less inundation is better. Based on this idea, a merit matrix [Eq. (1)] is designed by jointly considering power and average channel slope. The concept also motivates the choice of an upper bound of hydraulic head using the FEMA 100-year floodplain. However, inundation is only one way that a new hydropower development may impact the environment. A simplified merit matrix defined in Eq. (1) can help identify stream reaches with less inundation, but these may not represent the most environmentally friendly location. The design of a full merit matrix is challenging because it should include hydrologic, hydraulic, environmental, economic, social, and cultural factors for optimization. This requires further exploration in following studies.

Acknowledgments

This research was sponsored by the US Department of Energy's Office of Energy Efficiency and Renewable Energy, Wind and Water Power Technologies Program. Support from California State University–Fresno is also acknowledged. This paper was co-authored by employees of Oak Ridge National Laboratory, managed by UT Battelle, LLC, under contract DE-AC05-00OR22725 with the US Department of Energy. Accordingly, the publisher, by accepting the article for publication, acknowledges that the United States government retains a nonexclusive, paid-up, irrevocable, worldwide license to publish or reproduce the published form of this manuscript, or allow others to do so, for United States government purposes.

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