MINISTERE DE L'ENSEIGNEMENT SUPERIEUR
ET DE LA RECHERCHE SCIENTIFIQUE

Felix Houphouët-Boigny University

UNITE DE FORMATION ET DE RECHERCHE
SCIENCES DES STRUCTURES DE LA
MATIERE ET DE TECHNOLOGIE

RÉPUBLIQUE DE CÔTE D'IVOIRE
UNION - DISCIPLINE - TRAVAIL

No : 837

INTERNATIONAL MASTER PROGRAM

IN RENEWABLE ENERGY AND GREEN HYDROGEN

SPECIALITY: GEORESOURCES (WATER/WIND) AND GREEN HYDROGEN TECHNOLOGY

MASTER THESIS

Topic:

Modelling of Hydropower Potential over Europe

Presented on 25th September 2025 by:

Biran Mbye

JURY

Dr. ZORO Georgina Emma	**President**	Université Félix Houphouët-Boigny
Dr. TOUALY Élisée	**Examiner**	Université Félix Houphouët-Boigny
Dr. DJAKOURE Sandrine	**Supervisor**	Université Félix Houphouët-Boigny
Prof. Harrie-Jan Hendricks-Franssen	**Co-Supervisor**	Forschungszentrum - Jülich
Dr. Bibi S. NAZ	**Co-Supervisor**	Forschungszentrum - Jülich

Academic year: 2024-2025

DEDICATION

This thesis is dedicated to my beloved family, whose unwavering support, patience and love have been my constant source of strength and inspiration. Their support and words of encouragement have been my main source of strength and motivation throughout this programme. To all my friends who have been a strong pillar of support during this academic journey. Their encouragements and moments of laughter and support kept propelling me through even through very difficult moments. Your belief in me and your sacrifices have made this achievement possible. This academic journey was a testament to our shared resilience and commitment.

ACKNOWLEDGEMENTS

This thesis would not have been possible without the invaluable support, guidance, and contributions of numerous individuals and institutions. I extend my deepest gratitude to all who have supported me throughout this academic journey. First and foremost, I wish to thank the funders, German Federal Ministry of Education and Research and West African Science Service Center on Climate Change and Adapted Land Use (WASCAL) for providing me with the scholarship that made this academic pursuit a reality. Their commitment to fostering research and education in the west African region is truly commendable.

I also extend my sincere appreciation to the President of Universite Felix Houphouet Boigny for the honour of receiving my certificate from the esteemed institution. My heartfelt thanks go to the Director and Deputy Director of WASCAL Abidjan, for their continuous support. I am deeply grateful to the Coordinator of the H2 Programme, Professor Ferdinand Fassinou, and the Scientific Coordinator, for their crucial contributions.

I am immensely grateful to the President of Université Abdoumoumouni, and Université de Lomé for the unwavering support provided during the first and second semesters. My gratitude goes to the Administration of Forschungszentrum for providing me with the opportunity to gain invaluable practical experience and knowledge. I would like to express my profound thanks to the Director of WASCAL at The University of Abdoumoumouni, Prof. Rabani ADAMOU, for his guidance and mentorship.

My sincere thanks to my Supervisor, Dr. Sandrine Djakouré and co-supervisor, Prof. Dr. Harrie-Jan Hendricks Franssen, for his invaluable advice and expertise. I would like to express special thanks my daily supervisor, Dr. Bibi S. NAZ, for her continuous support and hands-on guidance, her exceptional supervision, insightful critiques, and for inspiring me to think critically and push the boundaries of my research. Her contribution to my thesis cannot be over emphasized. Sincere thanks to Dr. Shuying CHEN for her efforts in organizing meetings and ensuring seamless communication throughout the process. I also thank members of the Jury for their time and careful consideration of my work. My appreciation to the Directors of the IBG3 institute, for providing me with a conducive environment to produce such work.

A special thanks to the resolute team members from Niger who were involved during the first and second semesters of my programme. Finally, I want to express my gratitude to my family and friends for their constant encouragement, love, and unwavering belief in me. Their support has been a source of strength throughout this journey.

ABSTRACT

This thesis explores the technical hydropower potential over Europe, analysing the complex interplay between hydrology, climate, and operational strategies. Using geospatial and hydrological modelling, the study processes Digital Elevation Models and Community Land Model (CLM5) data to estimate runoff and calculate hydropower generation for sixteen upstream areas of hydropower dams across a 25-year period (2000-2024).

The results show catchment area, discharge, power a strong relationship between water discharge and power produced but the two variables are not always directly correlated. This is exhibited by a comparative analysis of a major drought year (2003), and a high-performance year (2024) reveals decoupling. In 2003, a severe reduction in discharge led to a direct and significant drop in power, confirming hydrology as the dominant limiting factor. However, the year 2024, which featured peak power generation, did not correspond to the highest discharge on record. This decoupling suggests that discharge does not instantly get converted to power meaning there could be a lag. In practice, strategic reservoir management, operational efficiency, and other non-hydrological factors are critical for maximizing energy output in large-scale systems.

The research provides a methodology for assessing hydropower potential on a regional scale and highlights the need for future models to integrate operational and economic variables. As a main renewable energy source, the discharge and volume results obtained from this research are crucial for integrating hydropower plant and reservoir management practices that could help improve generation for in a changing climate. The proposed methodology could also be applied in other regions globally, especially where dam regulation data are scarce such as in Africa.

Key Words: Hydropower; Hydrology; Climate Change; Renewable Energy; Geospatial Modelling

RÉSUMÉ

Ce mémoire explore le potentiel hydroélectrique technique en Europe, en analysant l'interaction complexe entre l'hydrologie, le climat et les stratégies opérationnelles. À l'aide de la modélisation géospatiale et hydrologique, l'étude traite les modèles numériques de terrain et les données du Community Land Model (CLM5) pour estimer le ruissellement et calculer la production d'énergie hydroélectrique pour seize zones d'Europe en amont de barrages hydroélectriques sur une période de 25 ans (2000-2024).

Les résultats montrent une forte relation entre le débit d'eau et l'énergie produite, mais les deux variables ne sont pas toujours directement corrélées. Cela est démontré par une analyse comparative d'une année de sécheresse majeure (2003) et d'une année de haute performance (2024) qui révèle cette nuance. En 2003, une réduction sévère du débit a entraîné une baisse directe et significative de la production, confirmant que l'hydrologie est le principal facteur limitant. Cependant, l'année 2024, qui a connu une production d'énergie maximale, ne correspond pas au débit le plus élevé jamais enregistré. Ce découplage suggère que le débit n'est pas instantanément converti en énergie, ce qui pourrait indiquer un certain décalage. Dans la pratique, la gestion stratégique des réservoirs, l'efficacité opérationnelle et d'autres facteurs non hydrologiques sont cruciaux pour maximiser la production d'énergie dans les systèmes à grande échelle.

La recherche fournit une méthodologie pour évaluer le potentiel hydroélectrique à l'échelle régionale et souligne la nécessité pour les futurs modèles d'intégrer des variables opérationnelles et économiques. Les débits obtenus de cette recherche sont essentiels pour intégrer des pratiques de gestion des centrales hydroélectriques et des réservoirs qui pourraient contribuer à améliorer la production dans un climat en évolution. La méthodologie proposée pourrait également être appliquée dans d'autres régions du monde, notamment là où les données de régulation des barrages sont rares, comme en Afrique.

Mots-clés : Hydroélectricité ; Hydrologie; Changement climatique; Énergie renouvelable; Modélisation géospatiale

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF ACRONYMS AND ABBREVIATIONS

.csv	Comma-Separated Values file format
.xlsx	Excel file format
ArcGIS Pro	Geographic Information Systems software
AW3D	ALOS World 3D (a Digital Surface Model)
AW3D-30m	ALOS World 3D – 30 meters
CLM5	Community Land Model 5
DEM	Digital Elevation Model
DHM	Digital Height Model
DSM	Digital Surface Model
DTM	Digital Terrain Model
DWD	Deutscher Wetterdienst (German Meteorological Service)
EHA	Existing Hydropower Assets
EIA	U.S. Energy Information Agency
ENSO	El Niño-Southern Oscillation
EU	European Union
G3WBM	Global Geo-referenced Water Body Map
GDAL	Geospatial Data Abstraction Library
GeoDAR	Georeferenced Global Dams and Reservoir
GHG	Greenhouse Gas
GIS	Geographic Information System
GLAS	Geoscience Laser Altimeter System
GloHydroRes	Global Hydropower and Reservoir
GranD	Global Reservoir and Dam
GRASS	Geographic Resources Analysis Support System
GSP	Graduate School Program
H2	Hydrogen
IBT	Inter-Basin Transfer
ICESat	Ice, Cloud, and land Elevation Satellite
IDL	Interactive Data Language
IRENA	International Renewable Energy Agency
J	Joule
JAMSTEC	Japan Agency for Marine-Earth Science and Technology
JAXA	Japan Aerospace Exploration Agency
JRC	Joint Research Centre
kg/m^3	Kilograms per cubic meter
km^2	Square kilometers
KW	Kraftwerk (German for power plant)
m.a.s.l.	Meters above sea level
m/s	Meters per second
m	Meter
m^3/s	Cubic meters per second
MERIT	Multi-ErROR-Removed Improved-Terrain (a Digital Elevation Model)
MOSART	Model for Scale Adaptive River Transport
MW	Megawatt
NASA	National Aeronautics and Space Administration

NSIDC	National Snow and Ice Data Center
PSP	Pumped-Storage Plants
QGIS	Quantum Geographic Information System
RePP	Renewable Power Plant database
ROR	Run-of-River (plants)
RSHP	Reservoir-Storage Hydropower Plants
SHP	Small Hydropower stations
SRTM	Shuttle Radar Topography Mission
SRTM3	Shuttle Radar Topography Mission 3
SWAT	Soil and Water Assessment Tool
UNFCCC	United Nations Framework Convention on Climate Change
U-Tokyo	University of Tokyo
WASCAL	West African Science Service Centre on Climate Change and Adapted Land Use
WGS	World Geodetic System 84
WRI	World Resource Institute

GENERAL INTRODUCTION

INTRODUCTION

Context and Motivation

As the global demand for renewable energy continues to rise in response to climate change and energy security concerns, hydropower continues to be a vital component of sustainable electricity production. Unlike intermittent sources such as wind and solar, hydropower offers dispatchable energy, grid balancing capabilities, and long-term storage options (Turner & Voisin, 2022). Globally, hydropower stands as a prominent renewable energy source and also one if not the oldest sources of renewable energy, providing a dependable way to generate electricity and lower greenhouse gas emissions (Kouadio et al., 2022). It accounted for approximately 16% of the world's total electricity production in 2020 and over 60% of global renewable electricity generation (Shah et al., 2025). The need to remedy climate change and the transition to clean energy systems justify the need to consider the important role of hydropower in Europe which accounts for 12% of the European Union’s net electricity of installed capacity of 152GW. Globally hydropower installed capacity is at 1,415GW (Ng et al., 2017; Gøtske & Victoria, 2021). Its pumped-storage and traditional reservoirs, notably including 46 GW of pumped-storage turbine capacity, provide almost all the European Union's electricity storage, vital for grid flexibility. Generating an estimated 300 TWh of electricity in 2023, hydropower held the European Union's second-highest share among renewable energy sources, behind only wind energy (Gøtske & Victoria, 2021). The envisioned pathway to climate neutrality by 2050 under the European Green Deal includes the combination of wind and solar energy, with hydropower's flexibility playing a supporting role. Hydropower is a substantial contributor to Europe's current electricity mix (16% in 2018) and is expected to maintain its importance. The growing integration of variable wind and solar power necessitates a shift in the operation of hydropower plants to provide essential grid balancing by increasing production during peak hours and pump storage plants uses the excess power during low demand to fill up the reservoir this is a very important in the energy balance system. On the other hand, certain hydropower installations can leverage the seasonal nature of wind and solar, enabling them to operate in a way that mirrors natural river discharge, which can be advantageous for river ecosystems (Gøtske & Victoria, 2021).

In Europe and other regions, there is a renewed interest in harnessing untapped hydropower potential, particularly in mountainous areas where higher elevations and steeper slopes create favourable conditions for reservoir development. This correlation arises from the fundamental geomorphological requirements of reservoir construction. However, maximizing this potential requires advanced modelling techniques that combine hydrological simulations, climate data, and geospatial analysis (Lehner et al., 2005).

In this context, this thesis seeks to explore a geospatial-hydrological analysis approach for estimating the hydropower potential of selected sites over Europe (Lehner et al., 2005)

Research Questions

1. How can we efficiently identify and quantify viable hydropower sites using publicly available geospatial and hydrological data?
2. Which methodology, climate model and hydropower datasets could be used for hydropower analysis across Europe?
3. To what extent can modelled runoff and flow accumulation data provide reliable estimates of technical hydropower potential?

These questions are addressed by setting the following research objectives:

Research Objectives

This thesis aims to assess the technical hydropower potential of selected dam upstream area across Europe using geospatial and hydrological data across varying years.

The specific objectives are:

1. To process and analyse hydrological and geospatial data, thereby extracting relevant features such as flow direction, flow accumulation and dam upstream area.
2. To estimate discharge and volumes using CLM5 runoff output data to calculate potential hydropower generation using known reservoir water heads
3. To apply and validate the methodology using actual dam information.

CHAPTER ONE:
LITERATURE REVIEW

Chapter I: LITERATURE REVIEW

1.1 Overall Context of Hydropower in Europe

The European hydropower sector is an evolving landscape, continuously shaped by a combination of economic, political, and environmental forces. This means that anyone involved, from energy companies to environmental groups, should be able to adapt to the evolving landscape of the energy sector. To address these changes effectively, it's crucial to understand Europe's energy system. However, a major driving force impacting the entire European energy sector is the need to mitigate climate change.(Wagner et al., 2019). The European Union (EU) has set ambitious climate and energy targets (like the 20-20-20 targets from 2007 and strategies for 2020, 2030, and 2050). These targets provide the legal framework for reducing carbon emissions in the energy system by increasing the use of renewable energy sources. Hydropower is recognized as the largest, most historically developed, and well-established renewable energy source, this makes it an important player in the transition to cleaner energy. Considering EU's renewable energy production, hydropower makes up 41.7% of it, this is a significant amount (Wagner et al., 2019).

In 2017, Europe's installed hydropower capacity was approximately 248.6 GW, about 600 TWh of electricity. The largest contributors to this capacity were Norway (31.8 GW), Turkey (26.7 GW), and France (25.5 GW). This is mainly due to favourable geographical conditions and the size and climate of these countries.

The proportion of national electricity generation from hydropower varies significantly across European countries, from nearly 100% (e.g., 98.3% in Norway) to much smaller percentages (e.g., 11.7% in the United Kingdom). Hydropower is highly efficient, boasting a high energy conversion rate and the best energy payback ratio (energy output compared to energy input over a project's life) among all electricity generation technologies(Wagner et al., 2019).

1.1.1 Challenges and Trends in Hydropower Expansion

While global hydropower has nearly doubled since 1990, Europe's increase has been only about a third. This slower growth is partly because many major hydropower projects in Europe were completed between 1920 and 1970, meaning a large portion (over 50%) of the hydropower potential is already in use. Further expansion in Europe is often complicated by conflicting interests related to energy policy, environmental concerns, and economic factors. Consequently, many hydropower projects are abandoned due to environmental and social worries, as well as high economic costs. It's important to note that the predicted hydropower potential and existing viable sites shouldn't be taken for granted. For instance, climate change is projected to decrease Europe's gross hydropower potential by 6%, with some southwestern and southeastern European countries facing declines of 20% to 50% in hydroelectric generation (Wagner et al., 2019). Figure 1 shows Hydropower's share of renewable and total installed hydropower capacity in European continent.

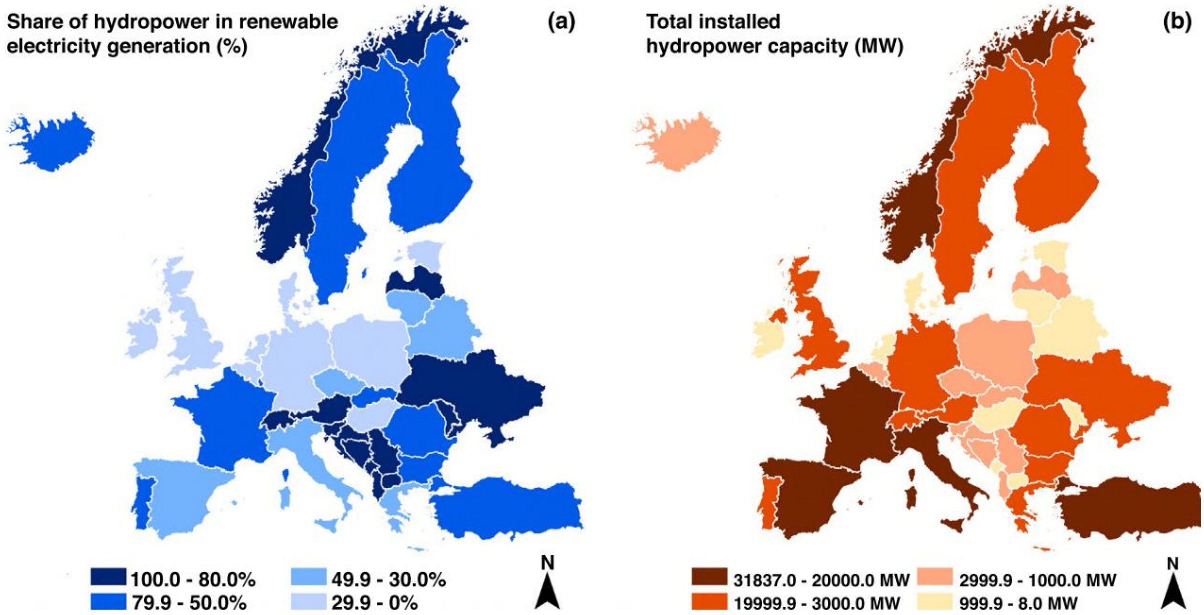


Figure 1: (a) Hydropower's share of renewable electricity in Europe (b) Total installed hydropower capacity in European countries (MW) Source: (Wagner et al., 2019).

1.1.2 Technological Developments

Pumped storage plants are particularly important for balancing the increasing number of variables, decentralized renewable energy sources like wind or solar power entering the electricity market. Their flexibility and economic efficiency have historically made them highly desirable. Despite recent economic challenges that have impacted the profitability of new pumped storage projects, there's still a strong trend towards new pumped storage projects in Europe. In fact, over half of the total hydropower capacity installed in Europe in 2017 came from pumped storage projects. However, new large run-of-river plants (over 10 MW) face difficulties because suitable river sections are often already in use or located in environmentally sensitive areas. Therefore, many European countries are focusing on upgrading and extending existing facilities to improve efficiency. Small hydropower plants (under 10 MW) are seen as having significant untapped potential in Europe, driven by political incentives and manageable economic risks, especially in less developed regions (Wagner et al., 2019).

1.1.4 Balancing Renewables and Grid Integration (10MW)

Hydropower, particularly reservoir-based systems, is increasingly important for balancing electricity grids with a growing share of variable renewables like wind and solar. This role helps mitigate renewable intermittency and reduce system imbalances, highlighting its growing operational significance as a flexibility asset. The transition to a decarbonized European energy system means hydropower operations will need to change, potentially with more rapid adjustments and seasonal variations in output (Gøtske & Victoria, 2021; Gøtske & Victoria, 2025).

1.1.5 Definition and Characteristics of Small Hydropower

Manzano-Agugliaro defines SHP as hydraulic power plants with less than 10 MW installed capacity, which is a common classification by international agencies. It explicitly states that hydropower is generated by the movement of water, often flowing through channels or pipes to turn a turbine. This description directly aligns with how run-of-river plants operate. The paper also notes that SHPs don't consume the water they use, which is a key characteristic of run-of-river systems, making them environmentally friendly (Manzano-Agugliaro et al., 2017). Hydroelectric energy is a reliable renewable source that doesn't cause pollution and has no fuel costs. Germany, Austria, and Italy are champions of SHP facilities. This data is crucial for establishing the existing landscape and scale of small hydropower, which directly informs the context of run-of-river plants within Europe (Manzano-Agugliaro et al., 2017).

1.2 Classification of Hydropower Plants

Hydropower plants can be classified according to how they utilize the inflow of water they receive. The classification often depends on whether the inflow must be used immediately or can be stored for later use. Based on this principle, hydropower systems are generally categorized as run-of-river, storage, or pumped-storage plants. There are other ways of distinguishing them, for example capacity and arrangement. Some hydropower plants consist of mixed systems like those that have storage and pumping systems but those can be generally referred to as storage hydropower plants. Generally, the reservoirs in the storage hydropower plants can store large volumes of water making them an energy bank that is readily available, whenever power is needed these can supply power for an extended period of time, making them a reliable balance for the intermittencies found in other renewable counterparts (Lehner et al., 2005). There are three main types of hydropower plants, with each category defined by its specific operational characteristics.

Reservoir-Storage Hydropower Plants (RSHP) as seen in figure 2, Often referred to as storage or dam hydropower, these facilities impound water behind dams in reservoirs, which can be either artificial or natural lakes. This stored water allows for the modulation of downstream flow and consequently, electricity generation is achieved through the turbine and generators.

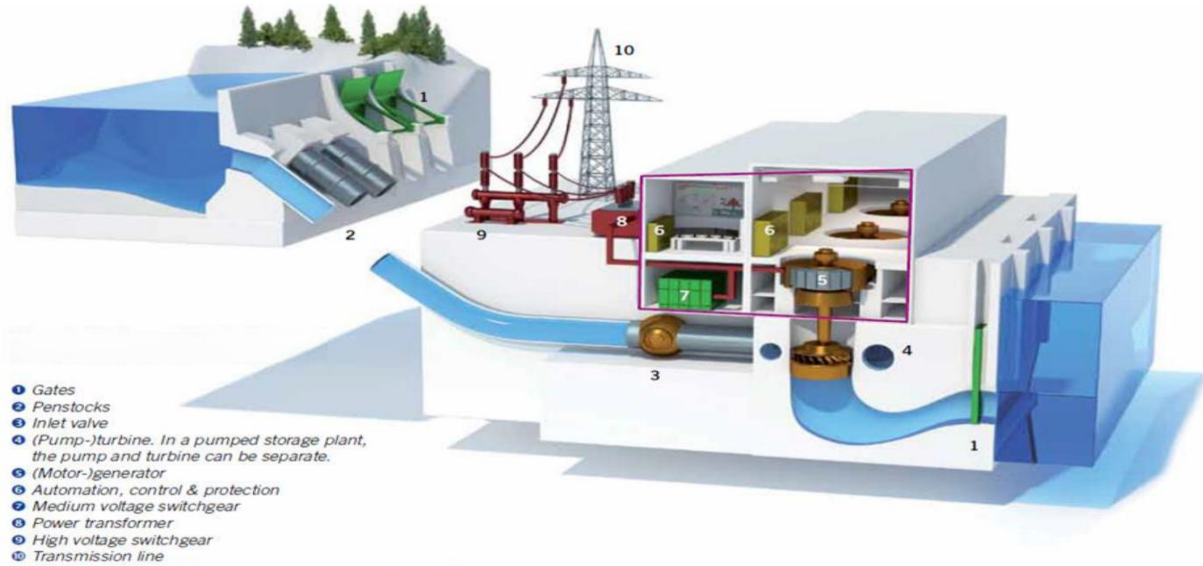


Figure 2: Layout of Reservoir-Storage Hydropower Plant. Source: (European Commission, Joint Research Centre, Quaranta, E., Georgakaki, A., Letout, S., Mountraki, A., Ince, E. and Gea Bermudez, J., 2024)

Run-of-River (ROR) Hydropower Plants as described in figure 3, utilizes the natural flow of a water body with minimal or no storage capacity. A plant is typically classified as ROR if its storage volume is less than the average daily inflow. Its simplicity makes it a favourable choice for this study.

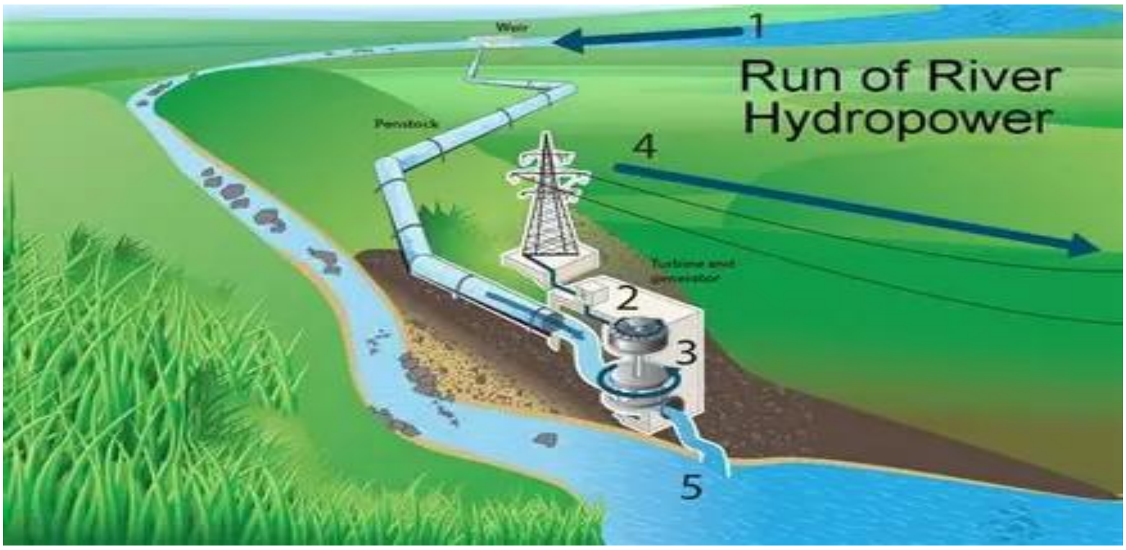


Figure 3: Layout of Run-of-River (ROR) Hydropower Plant

Source : https://www.cleanfuture.co.in/wp-content/uploads/2019/03/energy-hydro.jpg

Pumped-Storage Hydropower (PSH) as described in figure 4 below, generally consists of two reservoirs connected by a turbine and pump system. PSH systems are designed to pump water to an elevated reservoir during off-peak hours and release it to generate electricity when demand is high. This approach to energy storage is highly significant, accounting for more than 90% of the global capacity (European Commission et al., 2024).

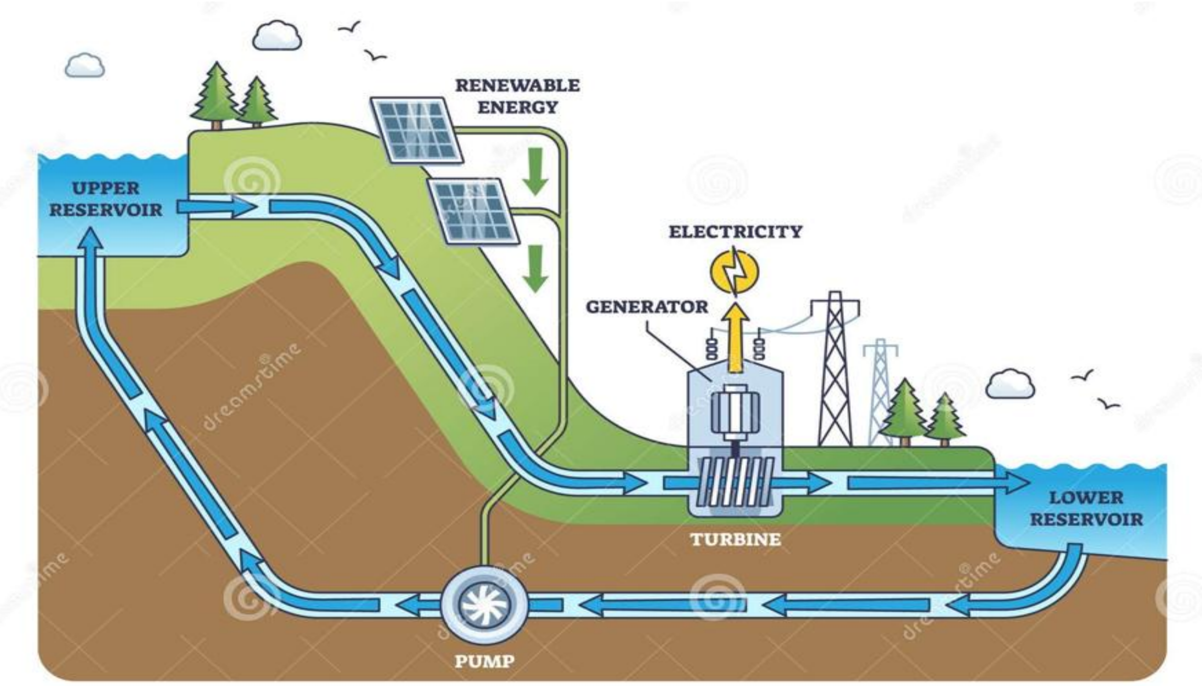


Figure 4: Layout of Pumped-Storage Hydropower (PSH)

Source : https://thumbs.dreamstime.com/z/pumped-hydropower-storage-hydro-electricity-production-outline-diagram-reservoir-generator-turbine-principle-scheme-269348193.jpg

In this context, run-of-river (ROR) hydropower systems have emerged as a viable and environmentally favourable alternative to large dam-based hydropower plants. ROR plants operate with minimal water storage and rely on the natural flow of rivers, which makes them less disruptive to local ecosystems and communities (Baird et al., 2024). However, despite these environmental benefits, ROR installations are susceptible to hydrological variability and may face operational limitations under changing climatic conditions (Ng et al., 2017).

1.3 Importance and Challenges of Run-of-River Plants

There's a growing need for clean, sustainable energy sources, which has encouraged the development of small run-of-river plants. These plants are often seen as a great solution because they can provide a long-lasting and affordable energy source with minimal environmental impact. In recent years, the number of very small hydropower plants (micro-hydro plants, up to 5 MW) has grown due to their efficiency and lower costs, especially in rural areas and small communities. However, despite their benefits, the full potential of small-scale hydropower isn't yet completely utilized. While promising, run-of-river plants do come with technical and economic challenges that need to be carefully managed to ensure they work reliably. The amount of power a plant can generate depends on the height difference of the water (hydraulic head) and the river's flow rate, which are both linked to the local landscape and how water moves through the river basin. A big part of developing these projects involves finding suitable locations. This "site identification" phase can be a significant part of the overall project costs (Ng et al., 2017).

1.3.1 Potential Site identification

Identifying the best places for run-of-river plants is crucial. Modern approaches often use tools like Geographic Information Systems (GIS) combined with hydrological models (which simulate how water moves through a river system) to find potential sites. This involves:

Analysing the landscape: Using digital elevation models (DEM) to map the river network, measure river lengths and slopes, and find elevations along the river. Considering river flow: Only selecting river channels with enough water flow to ensure sufficient power generation. Minimizing environmental impact and costs: Choosing sites where the water diversion and return points are close to each other (e.g., within 100 meters). This helps reduce the impact on river ecosystems and lowers pipeline installation costs. Modelling river flow: Using hydrological models like the Soil and Water Assessment Tool (SWAT) to accurately predict daily river flows, especially in areas where there isn't much existing data. Environmental and Economic Assessment**:** After potential locations are found, they undergo environmental and economic evaluations. This includes checking for environmental restrictions (like protected areas or habitats) and calculating how long it would take to earn back the investment (payback period). Sites in environmentally sensitive areas are often excluded or may face higher costs due to necessary protection measures (Sammartano et al., 2019).

1.3.2 Distinction of Hydro Power Plant based on capacity.

There is a further distinction of hydropower types based on power, this typically considers the hydropower plants large scale and small scale depending on the power variation. In the small hydropower category. Hydropower power plant with installed capacity of 1mw is considered as a mini hydropower plant. Hydropower power plants that are 100kw and below are micro and the 5kw capacity and are referred to as pico-Hydropower plant. It is important to note that the capacity of a hydropower plant doesn’t always correspond to the installed capacity, some hydropower plants have a magnificent perimeter as in tens of kilometre squares including their reservoir area while their installed capacity is considerably low others just cover a few square kilometres and possess an installed capacity way higher. The hydropower plants that are above 10mw are considered large in Europe. The hydropower plants that have installed capacity up to hundreds of megawatts are generally considered very large hydropower plants. This classification is not consistent when we consider different countries, like China, America, India and other countries (European Commission et al., 2024).

Table 1: Hydropower plant classification based on capacity.

Type	Capacity
Large-Hydro	More than 100 MW
Medium-Hydro	15 up to 100 MW
Small-Hydro	1 up to 15 MW
Mini-Hydro	Above 100 kW but below 1 MW
Micro-Hydro	From 5 kW up to 100 kW
Pico-Hydro	From few hundred watts up to 5 kW

1.4 Technological Progress in geospatial modelling for hydropower potential

Over the past two decades, the field of hydropower has undergone a substantial evolution, it has evolved from a focus on technology and resource exploitation to a more concise and integrated assessment of sustainability, climate variability, and geospatial modelling. It has made important contributions in addressing global concerns like climate change, environmental sustainability and recent power coupling methods. Despite being one of the oldest renewable energy technologies, its optimization and scrutiny for a better and more reliable source of energy remains critical. Hydropower development has undergone a notable transformation, progressing from simple run-of-river (ROR) installations to more complex storage and pumped-storage systems designed to enhance grid flexibility and resilience. ROR plants offer simpler and more affordable infrastructure and favoured for their lower environmental footprint, are increasingly scrutinized for their cumulative ecological impacts (Baird et al., 2025). The integration of hydrological models with geospatial analysis tools has revolutionized hydropower site assessment, particularly in regions with limited in-situ data. Kouadio et al. (2022) carried out an evaluation of hydropower potential of Côte d'Ivoire's White Bandama watershed. They used a technique called SWAT model conducted GIS working environment. Their research showed that land use, precipitation, and topography could be used to simulate runoff and infer generation capacity (Kouadio et al., 2022).

1.4.2 Climate Variability and Operational Implications

Hydropower generation is highly sensitive to climate variability such as drought and other large-scale patterns such as the El Niño–Southern Oscillation (ENSO). Ng et al. (2017) provided a global analysis of ENSO's influence on hydropower generation, revealing significant reductions in output during El Niño years, particularly in tropical and subtropical zones. Gøtske and Victoria (2021) extended this discussion to the European context, modelling the role of hydropower in future electricity systems with high shares of wind and solar. They found that hydropower, especially storage-based systems can mitigate renewable intermittency and reduce system imbalances. Their results underscore the growing operational significance of hydropower as a flexibility asset, not just a baseload resource.

These insights motivate the inclusion of climate signals in hydropower modelling and scenario planning, particularly for long-term infrastructure development under uncertain hydroclimatic futures.

1.4.3 Modelling Hydropower at Large Scales

The expansion of hydropower modelling from local project assessments to continental and global scales such as Europe, presents opportunities and challenges. Turner and Voisin (2022) reviewed methods for simulating hydropower generation at subcontinental to global scales, noting that while large-scale models often simplify reservoir operations, the trend is moving toward more physically consistent and data-driven approaches. The availability of standardized, global datasets, including GloHydroRes, Global Dam Watch (Lehner et al., 2024), and Shah et al.'s (2025), is helping to facilitate this transition. These resources reduce inconsistencies in dam attribute reporting, facilitate hydrological routing, and support integration with climate and energy models. Their availability represents a major advancement in reproducibility and scalability for research like my thesis, which targets multiple test sites using consistent methodologies.

1.4.4 Environmental and Socio-Ecological Considerations

Despite its renewable label, hydropower often comes at a substantial environmental cost. While ROR systems were initially believed to minimize ecological disruption, recent global reviews suggest otherwise. Baird et al. (2025) argue that ROR projects can lead to habitat fragmentation, disrupted sediment flows, and significant declines in aquatic biodiversity especially when multiple plants are installed sequentially along a river (Sammartano et al., 2019). These impacts demand greater integration of environmental flow assessments and spatial planning. Future hydropower development, whether ROR or storage-based, must be guided by ecological thresholds and mitigation strategies to ensure long-term sustainability. This need aligns with the increasing emphasis in research on balancing energy development with conservation outcomes (Baird et al., 2024).

1.5 Research Gaps and Limitations of Existing Studies

Analysing hydropower potential requires information from both reservoir point of view as well as hydropower plant infrastructure. A significant challenge in hydropower modelling and assessment has been the lack of integrated, open-source datasets and methodology to support the use of such dataset. Usually, hydropower plant data lacks most of the important reservoir data necessary for power potential estimation likewise reservoir data mostly lack valuable plant information this creates a gap for such analysis (Shah et al., 2025). New datasets like GloHydroRes aim to bridge this by combining plant attributes like head with reservoir characteristics like volume and catchment area (Lehner et al., 2024). When simulating hydropower at subcontinental to global scales, models often simplify how reservoirs are operated. There's a clear trend towards developing more physically consistent and data-driven approaches to overcome these simplifications and improve accuracy (Turner & Voisin, 2022). Hydropower generation is highly sensitive to climate variability, like droughts and large-scale patterns such as the El Niño–Southern Oscillation (ENSO), which can significantly reduce output (Ng et al., 2017). This sensitivity underscores the critical need for climate-informed generation forecasting and scenario planning, especially for long-term infrastructure development under uncertain hydroclimatic futures (Ng et al., 2017).

1.6 Outlook and Emerging Research Directions

The development of global, standardized datasets like GloHydroRes and Global Dam Watch is a major step forward (Shah et al., 2025; Lehner et al., 2024). These resources reduce inconsistencies in reporting, improve hydrological modelling, and make it easier to integrate hydropower data with climate and energy models. This shift supports more reproducible and scalable research, which is directly relevant to my thesis (Turner & Voisin, 2022). As Europe aims for a decarbonized energy system, hydropower, particularly flexible storage-based systems, will become even more crucial. It's expected to play a vital role in balancing the increasing amounts of variable wind and solar power, leading to higher demands for its flexibility and responsiveness (Gøtske & Victoria, 2021; Gøtske & Victoria, 2025). Future hydropower development must deeply integrate climate signals into modelling and scenario planning (Ng et al., 2017). This is essential for building resilient infrastructure that can adapt to changing water availability and extreme weather events caused by climate change.

Partial Conclusion

This literature shows that the field of hydropower is an evolving field of energy that may not only be limited to energy generation but also consist substantial amount of social and environmental aspect. The evolution from simple run-of-river plants to more complex systems has been driven by advances in integrated geospatial and hydrological modelling. Global datasets have also improved hydropower planning and simulation. Nonetheless, serious concerns remain over climate impacts and environmental degradation. This underscores the need for more sustainable and adaptive development agenda.

This thesis contributes directly to this contemporary landscape by applying spatial-hydrological tools and climate-informed assessments to evaluate hydropower potential in European catchments, an approach that reflects both technical innovation and policy relevance

CHAPTER TWO: MATERIALS AND METHODS

CHAPTER II: MATERIALS AND METHODS

Introduction

This chapter delineates the geospatial-hydrological modelling framework developed for assessing hydropower potential across Europe. This methodology systematically integrates diverse spatial datasets and leverages robust open-source geographic information systems (GIS) for spatial operations, supplemented by programmatic scripting for detailed analytical computations. A pivotal component of this framework is the GloHydroRes dataset (Shah et al., 2025). chosen specifically to resolve a common challenge in hydropower research, the fragmentation of existing open-source data, where plant information frequently lacks reservoir details and vice versa. By consolidating diverse global hydropower plant and reservoir data, GloHydroRes furnishes comprehensive attributes, including location, effective head, plant type, and key reservoir characteristics such as dam height, volume, and area (Shah et al., 2025). The QGIS software was used to virtually identify dam location using GloHydroRes data.

2.1 Study Area

The geographical scope of this study encompasses the European continent as shown in figure 5, covering all countries and their respective river basins within the approximate geographical boundaries of 35°N to 72°N latitude and 10°W to 60°E longitude. This vast and hydrologically diverse region was selected due to its significant existing hydropower infrastructure, its ambitious renewable energy targets under the European Green Deal, and its substantial remaining untapped hydropower potential and data availability (Gøtske & Victoria, 2021). Topographically, Europe presents a varied landscape which is crucial for hydropower development, characterized by extensive mountain ranges such as the Alps, Pyrenees, Carpathians, and Scandinavian Mountains. These elevated regions, with their steep gradients and substantial precipitation, are natural facilitators for high head hydropower installations. Hydrologically, the continent is crisscrossed by numerous major river systems, including the Danube, Rhine, Rhône, and Elbe, exhibiting diverse flow regimes influenced by varied climatic conditions, from the Mediterranean in the south to temperate regions in the north. This climatic and topographic heterogeneity results in diverse hydrological patterns across Europe, directly impacting water availability and the characteristics of potential hydropower sites (Paprotny & Morales-Nápoles, 2017).

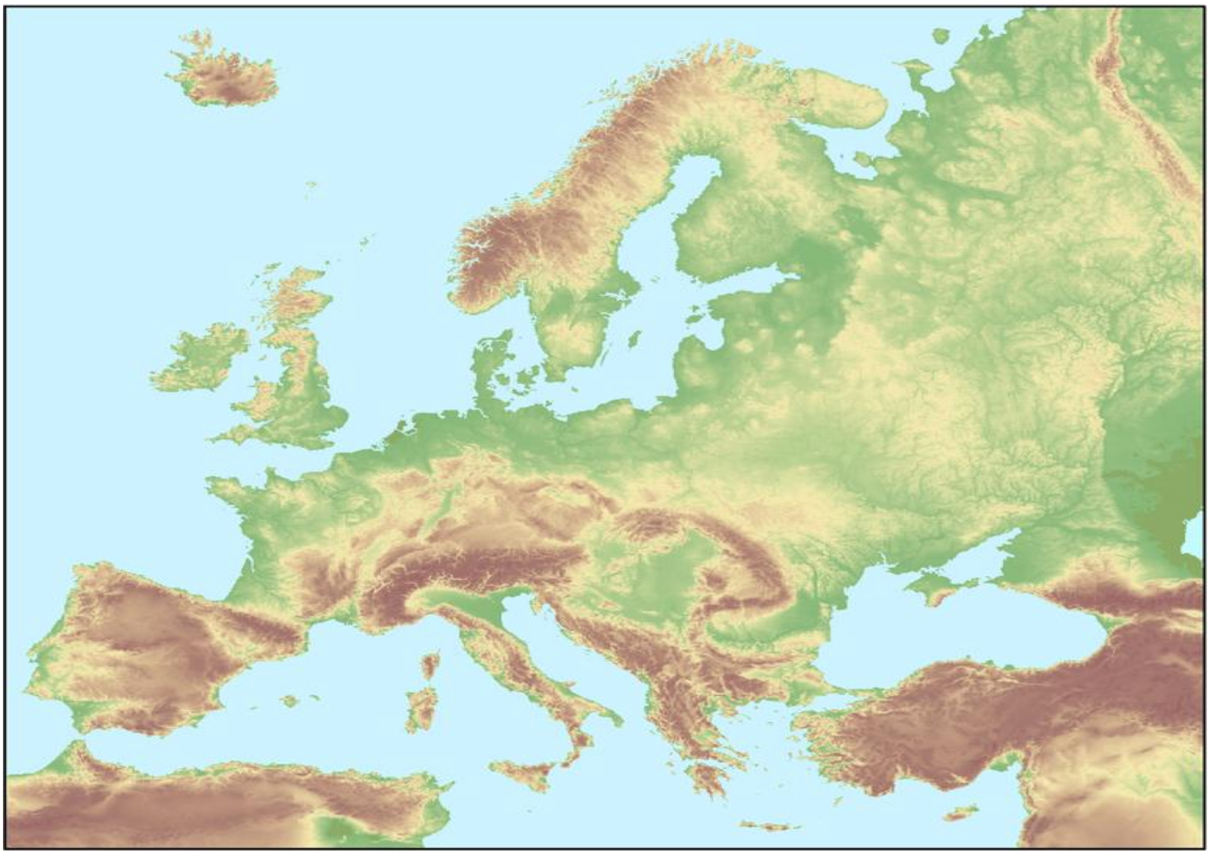


Figure 5: The geographical scope of the study area.

Source:https://www.eea.europa.eu/data-and-maps/figures/elevation-map-of europe/europeelevation.eps/image_large

The climatic and topographic diversity of the European continent give rise to several river types and hydrological patterns. These includes the snowmelt-dominated systems in alpine and northern regions to predominantly rain-fed rivers in temperate zones. Spatially, Europe generally exhibits higher average precipitation and subsequent runoff in its western and mountainous areas, this trend decreases heading towards the eastern and southern parts of the continent (Wrzesiński, 2013). Table 2 provides a comprehensive overview of the hydropower dams selected for this study. The information includes the name of each dam, its assigned GloHydroRes ID, the country in which it is located, and the specific river basin it belongs to. This provides essential insights into the geographical distribution of the dams and their associated river basins.

Table 2: List of dams and their corresponding river basins selected for this study across Europe.

Watershed	GloHydroResID	Dam Name	Country	River Basin
1	GHR03122	Tuilières	France	Dordogne River basin
2	GHR00249	Kraftwerk Alberschwende	Austria	Bregenzer Ache basin
3	GHR03113	Teillet-Argenty	France	Le Cher River basin
4	GHR03067	Saint-Gervais-d'Auvergne	France	La Sioule River basin
5	GHR03208	KW Öpfingen	Germany	Danube River basin
6	GHR03922	Signayes	Italy	Marmore River basin
7	GHR03134	Villarodin	France	Arc River basin
8	GHR03798	Farigliano	Italy	Tanaro River basin
9	GHR03037	Prayssac	France	Lot River basin
10	GHR03142	Voutezac	France	Vézère River basin
11	GHR03207	KW Gundelsheim	Germany	Neckar River basin
12	GHR05886	Trangfors	Sweden	Ljungans River basin
13	GHR05832	Motala	Sweden	Motala Ström basin
14	GHR05583	CIJARA 1	Spain	Guadiana River basin
15	GHR05569	Bolarque 2	Spain	Tagus River basin
16	GHR06253	Kiev	Ukraine	Dnieper River basin

2.2 Primary Datasets Used

For the modelling framework, the following primary datasets were used:

1. Global Hydropower and Reservoir (GloHydroRes) Dataset (Shah et al., 2025).
2. Multi-ErROR-Removed Improved-Terrain (MERIT) DEM (topography, longitude, latitude) (multi-erROR-removed improved-terrain dem.)
3. Community Land Model version 5 (CLM5) Derived Data (Hydrological Runoff) (Lawrence et al., 2019).

2.3 Global Hydropower and Reservoir Dataset

GloHydroRes dataset shown in figure 6, is a comprehensive global dataset designed to bridge a significant gap in existing open-source data by integrating information on both hydropower plants and their associated reservoirs. Prior to its development, publicly available datasets often lacked a unified view, with hydropower plant datasets missing reservoir details and vice versa. This integration is crucial for analysing the impacts of drought and climate change on hydropower potential and for improving hydropower generation modelling at the plant level.

Figure 6: ROR Dams over Europe from GloHydroRes dataset.

Containing data on 7,775 hydropower plants across 128 countries, the GloHydroRes dataset's quality was validated by comparing its figures to those from the EIA (2022) and IRENA (2023). It includes about 81% of global installed hydropower capacity. With dams such as run-of-river (ROR), storage (STO), pumped storage (PS), and canal plants, out of this, 3,237 (41.6%) are ROR plants and 2,658 (34.2%) STO plants.

Figure 6 above shows ROR hydropower plants over Europe. GloHydroRes includes a wide array of attributes for both hydropower plants and their linked reservoirs. These include, but are not limited to, data on the plant's location (latitude, longitude), its installed capacity (MW), and its type. The data also covers the dam and reservoir location, dam height (m), reservoir depth (m), reservoir area (km^2), and reservoir volume (km^3). The dataset also identifies 170 hydropower plants impacted by Inter-Basin Transfer (IBT) projects. The dataset was compiled by combining various existing open-source datasets. Hydropower plant data was sourced from datasets such as the World Resource Institute (WRI), Existing Hydropower Assets (EHA), Renewable Power Plant database (RePP), and JRC hydropower database. Reservoirs were linked to corresponding hydropower plants using datasets like the Global Reservoir and Dam (GranD), Georeferenced Global Dams and Reservoir (GeoDAR), and HydroLAKES, prioritizing GranD and GeoDAR for their detail, followed by HydroLAKES (Shah et al., 2025).

The GloHydroRes dataset's quality was verified by aggregating installed capacity at a country level and comparing the results to data from international sources like IRENA (2023) and the

EIA (2022). The GloHydroRes dataset is publicly available in Excel (.xlsx) and Comma-Separated Values (.csv) formats through the Zenodo open-source platform(Shah et al., 2025)

Figure 7 below shows the Global coverage and distribution of GloHydroRes dataset.

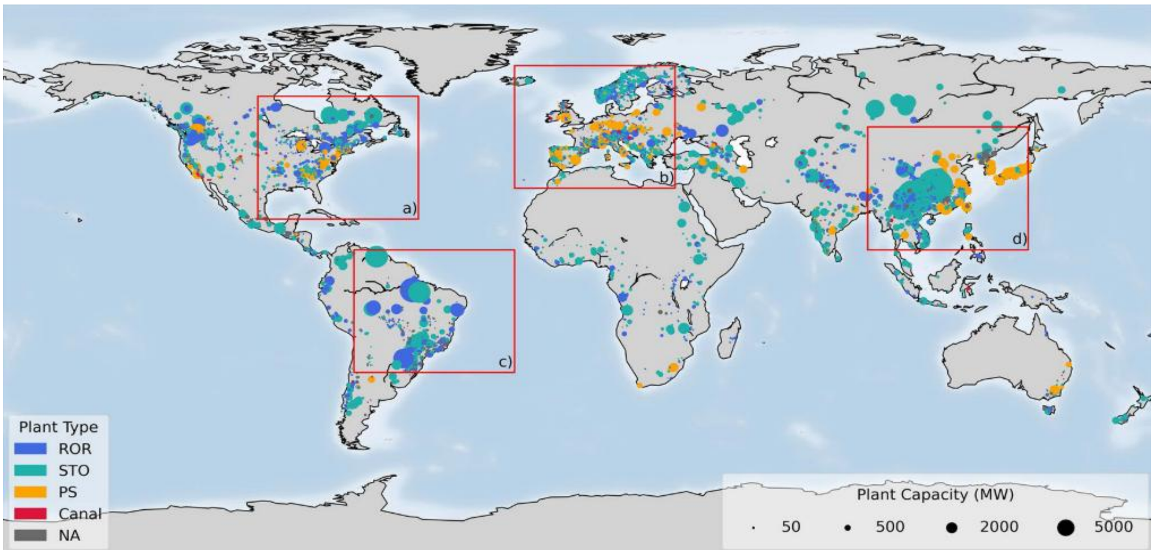


Figure 7: Global coverage and distribution of GloHydroRes dataset

Source: (Shah et al., 2025)

2.4 The Multi-Error-Removed Improved-Terrain Digital Elevation Model

In this study, MERIT (DEM) was used to represent the shape and features of the land. A DEM is essentially a detailed digital map that uses a system of small parts to show the unevenness of the terrain, like mountains and valleys. It can be used to visualize geographical features and understand the flow of water. The MERIT DEM as shown in figure 8 below, is a highly accurate global model that was created to fix errors found in older DEMs. It was developed by combining and improving data from three main sources: the NASA SRTM3 DEM, the JAXA AW3D-30m DEM, and the Viewfinder Panoramas' DEM. Scientists removed common Errors such as height biases and a grainy "noise" that can affect the data. They also used supplementary datasets, including information from NASA and others, to correct for things like tree height. Because of these corrections, the MERIT DEM is much more reliable, especially in flat areas like major floodplains (such as the Niger and Nile rivers) where older models were often inaccurate. This improved accuracy allowed for a clearer and more precise representation of the landscape, making it a valuable tool for my research.

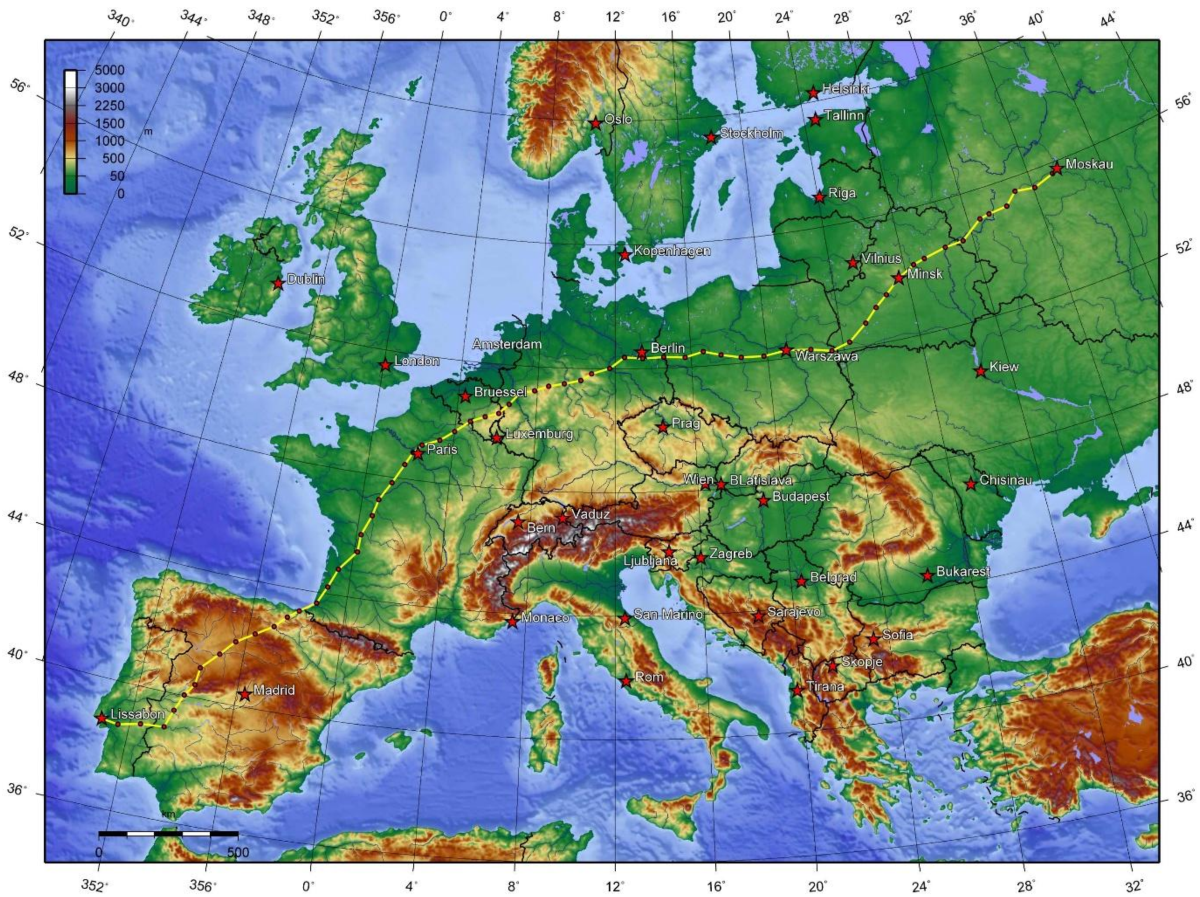


Figure 8: Topographic map of Europe showing elevation differences in meters above sea level. Source: Wikimedia Commons (Europe Topographic Map, 2024).

2.5 Community Land Model version 5 (CLM5) Derived Data

This study relies heavily on data from the Community Land Model version 5 (CLM5), which functions as the terrestrial component of the broader Community Earth System Model (CESM2). CLM5 is a detailed model that simulates land surface processes, including water flow, plant life, and how humans manage land. The CLM5 data are highly relevant for this analysis of hydropower potential in Europe, provided hydrological variables such as surface runoff at a spatial resolution of 3 km. The model's input data are derived from updated satellite observations and reanalysis products, ensuring accurate representation of topography and land use. Hydrological Runoff Output: The runoff data I used in this study comes directly from CLM5 simulations. This model is equipped with advanced methods for simulating runoff, especially through the Model for Scale Adaptive River Transport (MOSART). MOSART uses a standard method (Manning's equation) to calculate how water flows from hillsides to smaller streams and then to main rivers. CLM5's full approach to water movement includes detailed ways to show soil wetness, how snow behaves, and how groundwater interacts with surface water. All these parts help create the runoff data. It's important to know that the runoff from standard CLM5 simulations mainly shows natural water flow. This means it models how water moves without directly including human actions like large dam operations or water diversions. The monthly runoff data I used covers the period from 2000 up to 2024 and is provided on a yearly basis (Lawrence et al., 2019).

2.6 Methodological Analysis

2.6.1 Geospatial Analysis and Hydrological Feature Extraction

This initial phase of the methodological analysis is focused on QGIS-based Geospatial Pre-processing and Data Integration to prepare the raw topographical data and extracting essential hydrological features necessary for the hydropower potential assessment. This process primarily involved using the QGIS software, often leveraging its integrated SAGA GIS tools for terrain analysis.

Digital Elevation Model (DEM) into QGIS was loaded as a TIF file containing topographical elevation, longitude, and latitude information. While the file held other variables, I specifically focused on these key topographic data points for my work. Once loaded, I set the projection of this raster file to EPSG:4326 (WGS84). Following this, I defined my study domain.

Hydrological feature extraction began with processing the DEM. Using the SAGA GIS tools available within QGIS, the Fill Sinks (Wang & Liu) algorithm, this is the first step before any other step to make sure the terrain smooths out without deep depressions that may hinder water flow, it corrected any artificial depressions or sinks in the DEM that could impede accurate water flow simulation. The output from this process was a hydrologically conditioned DEM, which could also be referred to as the filled DEM. With the filled DEM ready, then the stream network layer was created. The Strahler Order tool was used for this, found within the SAGA GIS Terrain Analysis > Channels module. The filled DEM served as the input for this operation, which calculates the Strahler stream order for each segment of the flow network. To refine the stream network and focus on larger, more relevant channels, then further processed the output. Using the Raster Calculator tool in QGIS, for adjusting the stream orders (for example, by selecting Stream Network >=5) to filter out very small streams that, while present, do not significantly contribute to the main river channels for the purpose of this analysis.

Subsequently, the comprehensive river channel network was generated. Still within SAGA GIS, under the Channel Network and Drainage Basins tool, put the filled DEM as input. This process delineates the full river network, which was saved as Channel Network. This is useful for defining the upstream area of the dams.

It is important to note that while the Community Land Model version 5 (CLM5) is capable of simulating water transport through its routing module, this specific model setup did not utilize this feature. Consequently, it was necessary to delineate each watershed and manually calculate runoff to discharge. This step was crucial for the methodology, as it allows to derive the necessary flow data for the hydropower potential calculations, a step that would have been automated if the model had been run with the routing module enabled.

Watershed delineation is essential for defining the exact geographical area that contributes water to a dam, which is the foundational step for accurately calculating a hydropower plant's potential. For this, I used the Upslope Area tool in QGIS. I delineated several catchments within the available DEM over Europe by inputting specific longitude and latitude coordinates. With the filled DEM as the input, running this command generated the delineated catchments for these specified points. The initial output of the catchment delineation process was a raster layer.

Apart from DEM processing, QGIS, in combination with the GloHydroRes dataset, made it possible to get more dam information through its data embedded link. The QGIS selection tools was used from the tool bar to interact with these dam points. This makes it possible to retrieve specific details linked to each dam directly from the dataset's attribute table.

Throughout these steps, several important layers were created, including the filled DEM itself, flow accumulation, flow direction, discharge, stream order, and river channels.

2.6.2 GRASS GIS-based Hydrological Feature Extraction

Due to the connectivity challenges observed with river network delineation in QGIS, I transitioned to GRASS GIS for the more robust and reliable execution of catchment delineation and comprehensive river network analysis. GRASS GIS proved to be superior in providing better connectivity and more coherent river networks. My GRASS GIS workflow began by setting up a new project. I carefully configured the project environment to ensure the correct projection, EPSG:4326 (WGS84), was applied. This was done within the GRASS working environment settings by creating a new map set and defining its projection. After setting up the environment, I loaded the DEM into GRASS GIS. Similar to the initial processing, the first step in GRASS GIS was to fill any depressions in the DEM. I navigated to the Raster menu, then Hydrologic modelling, and selected the Depression less map tool. My loaded DEM was the input for this tool, resulting in a hydrologically corrected "filled DEM" within the GRASS GIS environment.

Next, the flow accumulation was calculated as shown in figure 9 and flow direction as shown in figure 10 below. These essential tools are found under Raster -> Hydrologic modelling ->

Watershed analysis. the filled DEM was inputted into this tool, which then generated both the flow accumulation and flow direction layers. It was observed that the visualization of the flow accumulation layer in GRASS GIS, displayed on the canvas, showed the river network much more clearly and connectedly compared to QGIS. This improved representation was a primary reason for deciding to utilize GRASS GIS for these critical steps.

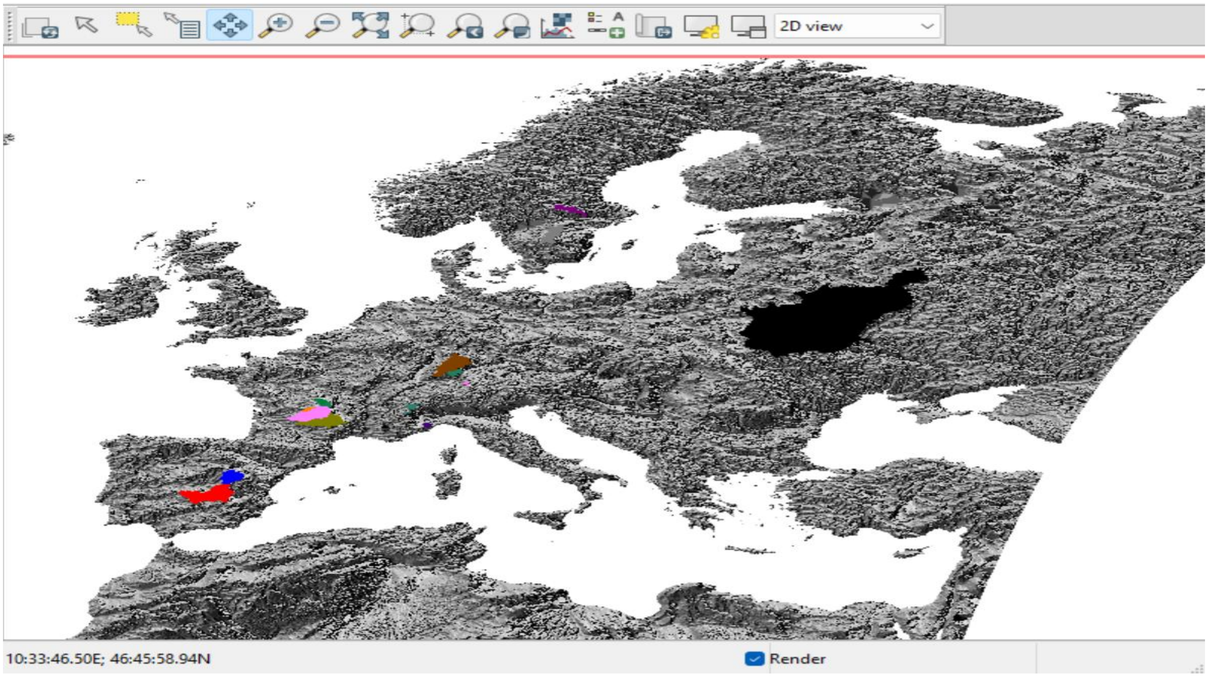


Figure 9: Flow Direction map.

After establishing the flow direction, the next step was to delineate the catchments as shown in figure 11 below. The GRASS GIS tool was used to create watershed basin from a drainage direction map, providing the previously generated flow direction layer as input. This allowed me to delineate the specific catchments needed for my analysis. Once individual catchments were delineated, they were combined into a single, cohesive mask. This was achieved by using the Raster menu, then overlay, and finally the PATCH tool, which merged all the separate delineated catchments.

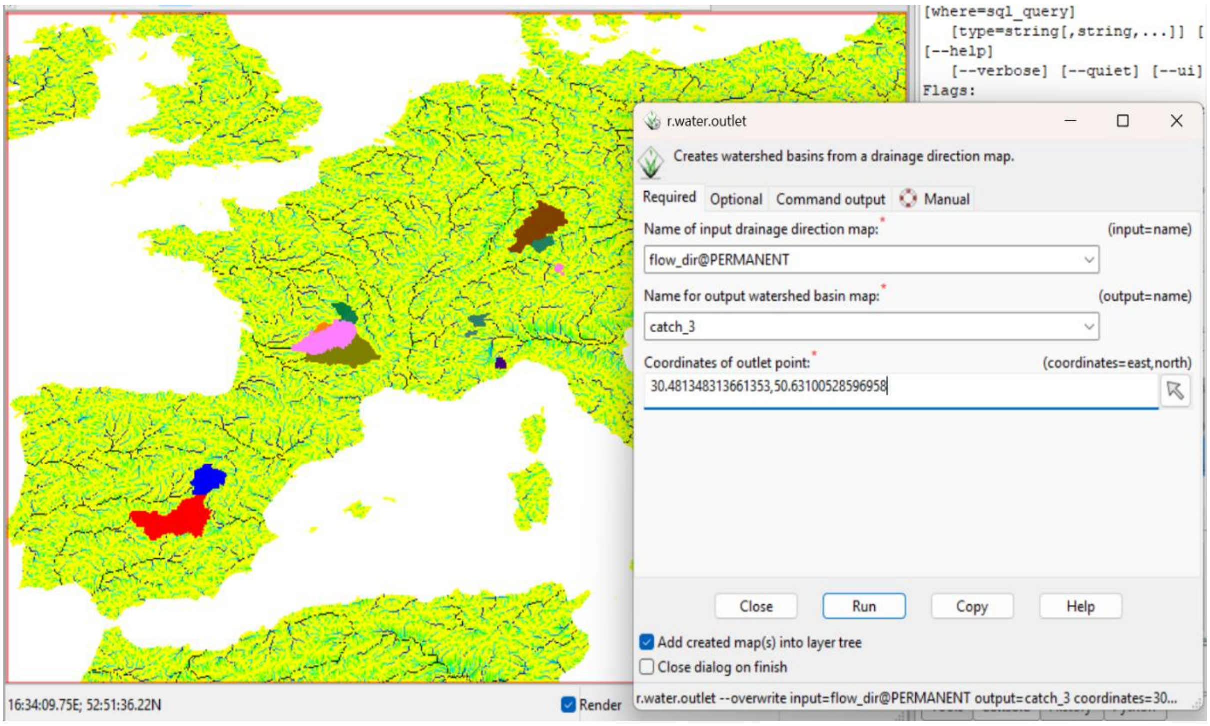


Figure 10: Flow Accumulation map.

For further analysis in Python, where vector data is preferred for hydropower potential calculations, the initial raster output of the delineated catchments from GRASS GIS was converted to vector format using appropriate raster conversion tools.

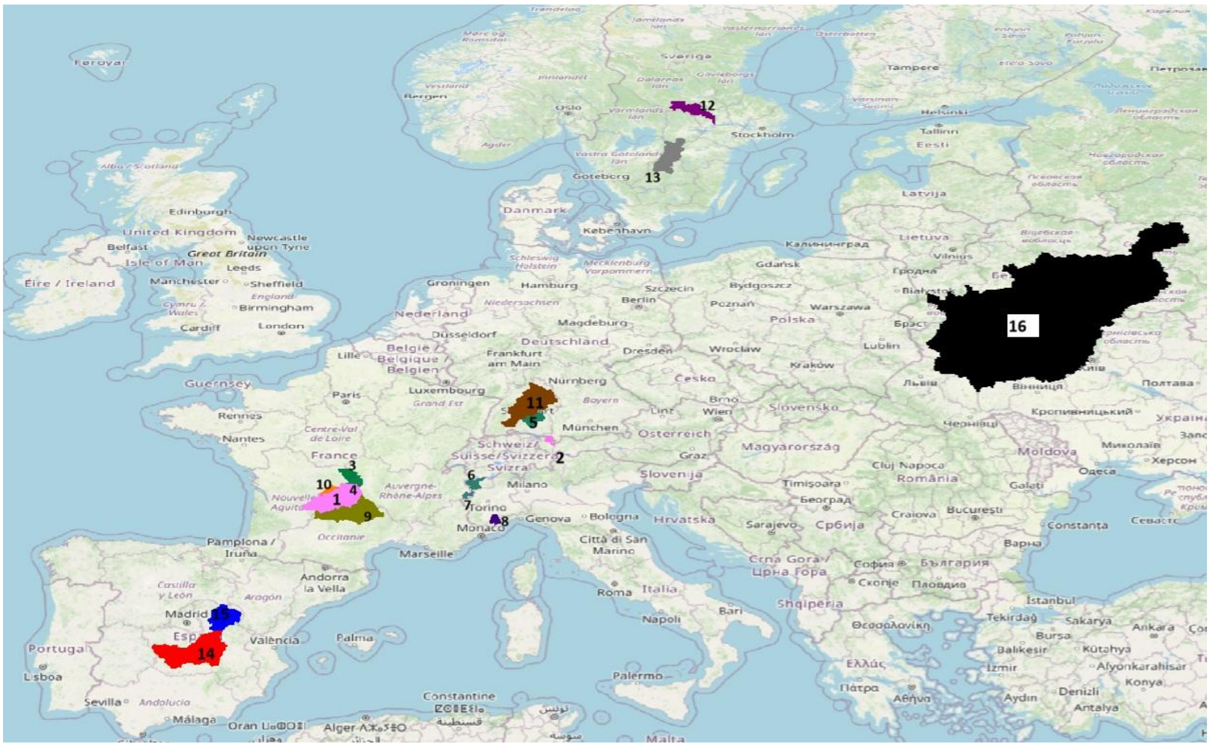


Figure 11: Delineated catchments over Europe.

2.6.3 Hydropower Potential Assessment using Python Tools

After preparing the geospatial data and analysing the runoff, the next step was to estimate the theoretical hydropower potential across different parts of Europe. This was achieved by developing and running a Python script that integrated the various datasets to calculate potential power generation.

Several specific Python tools (libraries) were used to get my analysis done such as xarray, NumPy, pandas, matplotlib etc.

2.6.4 CLM5 simulated Runoff-to-Inflow Conversion

The CLM5 runoff data came in units of millimetres per second (mm/day), then converted this into a more useful measure, cubic meters per second (m^3/s), which is called discharge. To do this, the runoff was multiplied by the land area of each watershed (in square meters) and adjusted the units correctly.

$$\text{Discharge } (\text{m}^3/\text{s}) = \frac{\text{Runoff } (\text{mm/day}) \times \text{Area } (\text{m}^2)}{86400} \qquad \text{Equation 1}$$

Once the discharge was obtained (equation 1), the total amount of water (volume in cubic meters) flowing through each watershed every month could be established. This was done by adding up all the discharge over that months' time (equation 2)

$$\text{Volume } (\text{m}^3) = \text{Runoff} \times \text{Area} \times \text{Days in Month} \times 10^{-3} \qquad \text{Equation 2}$$

Then, the standard formula was used to estimate how much power (in megawatts, MW) could theoretically be generated (equation 3).

$$P=\rho \cdot g \cdot Q \cdot H \cdot \eta \qquad \text{Equation 3}$$

Were:

- P – power (MW)
- ρ - water density (kg/m^3)
- g - gravitational acceleration (9.81 m/s^2)
- Q - in-flow of water (discharge) (m^3/s)
- H is the height of the dam water (m).
- H - efficiency.

The calculated data was sorted and grouped by month per watershed. This made it easy to compare how power changed throughout the year (seasonal patterns) and how it differed between various regions. The script also made plots that showed how discharge, water volume, and hydropower potential changed over time for each of the 16 watersheds. This helped me see the seasonal trends clearly. Connecting all my different data sources was a crucial part of the script. The watershed boundaries that were already created were used to create a special mask file. This mask was like a stencil that helped me pick out only the runoff data that fell exactly inside each watershed area. The creation of this mask was achieved by layering the watershed shapes on top of the CLM5 grid.

The script read the main runoff dataset (totrunoff_monthly.nc). This file provided detailed monthly runoff information from 2000 to 2024 across all the sixteen catchments. By using the watershed masks, the Python code could accurately extract and add up the runoff values for each specific watershed. This whole process of putting the data together meant that the model could correctly link the water flow information to the actual physical areas of each watershed.

The main outputs of the Python analysis provided were data frames of:

- monthly water flow (discharge in m^3/s) for every watershed.
- monthly total amount of water (volume in m^3) that moved through each watershed.
- monthly hydropower potential (in MW) that was calculated from the runoff data.

A set of graphs that showed the changes over time for water flow, volume, and power for all 16 watersheds.

These results were essential for me to understand how hydropower potential changes with the seasons and to compare different regions in this study, plots of special watersheds from different regions were made to compare their performance with their own performance history to be able to visualize how different hydrological years differ for each of the chosen regions.

Partial Conclusion

In conclusion, the GloHydroRes dataset, made it possible to locate ideal dam sites necessary for this research and to get more dam information through its data embedded link.

the analysis involved a strategic combination of both QGIS (for initial DEM preparation and dam data handling) and GRASS GIS (for robust river network and catchment delineation). These steps were necessary for the data processing which helped created layers such filled DEM, flow accumulation, flow direction, and river channels.

CHAPTER THREE:

RESULTS AND DISCUSSION

Chapter III: Results and Discussion

3.1 Catchment Area Analysis

The comparison of the calculated catchment areas with the reported actual catchment areas shows a strong correlation and confirms the accuracy of the methodology. As presented in table 3, the calculated values for all 16 dam sites are remarkably close to the actual data, with only a very small percentage of difference. This high level of agreement, particularly for geographically diverse locations across Europe, validates the effectiveness of the topographic data and the chosen calculation method. The minimal discrepancies observed are likely due to minor variations in the resolution of the DEM or slight differences in the geographical boundaries used for the official reports versus those derived from the model. Overall, the results demonstrate that the methodology provides a robust and reliable way to determine catchment areas, making the subsequent analyses and conclusions drawn in this thesis well-founded and credible. Table 3 below shows the observed catchment area vs the calculated catchment area for all the dams.

Table 3: Comparison of the calculated catchment area vs actual catchment area

Watershed	GloHydroRes ID	Dam Name	River Basin	Country	Observed Catchment Area (km²)	Calculated Catchment Area (km²)	Accuracy of calculated area
1	GHR03122	Tuilières	Dordogne River basin	France	11,500	11,529	Green
2	GHR00249	Kraftwerk Alberschwende	Bregenzer Ache basin	Austria	710	711	Green
3	GHR03113	Teillet-Argenty	Le Cher River basin	France	1,740	1,755	Green
4	GHR03067	Saint-Gervais-d'Auvergne	La Sioule River basin	France	1,250	1,242	Green
5	GHR03208	KW Öpfingen	Danube River basin	Germany	1,940	1,953	Green
6	GHR03922	Signayes	Marmore River basin	Italy	1,435	1,440	Green
7	GHR03134	Villarodin	Arc River basin	France	538	540	Green
8	GHR03798	Farigliano	Tanaro River basin	Italy	1,070	1,071	Green
9	GHR03037	Prayssac	Lot River basin	France	10,800	10,854	Green
10	GHR03142	Voutezac	Vézère River basin	France	673	675	Green
11	GHR03207	KW Gundelsheim	Neckar River basin	Germany	11,760	11,772	Green
12	GHR05886	Trangfors	Ljungans River basin	Sweden	2,750	2,754	Green
13	GHR05832	Motala	Motala Ström basin	Sweden	5,230	5,256	Green
14	GHR05583	CIJARA 1	Guadiana River basin	Spain	20,000	20,052	Green
15	GHR05569	Bolarque 2	Tagus River basin	Spain	7,100	7,146	Green
16	GHR06253	Kiev	Dnieper River basin	Ukraine	223,000	223,524	Green
Green - Good Estimation			Green (≤ 10% deviation)				
Yellow - Fair Estimation			Yellow (11–30% deviation)				
Red - Poor Estimation			Red (> 30% deviation)				

3.2 Comprehensive Analysis of Watershed Discharge (2000-2024)

This analysis provides a detailed examination of the monthly discharge data for the 16 watersheds as listed in table 3 over a 25-year period (2000-2024) as shown in figure 12 below. Understanding these long-term hydrological patterns, including magnitudes, seasonality, and inter-annual variability, is fundamental for accurately assessing and optimizing technical hydropower potential.

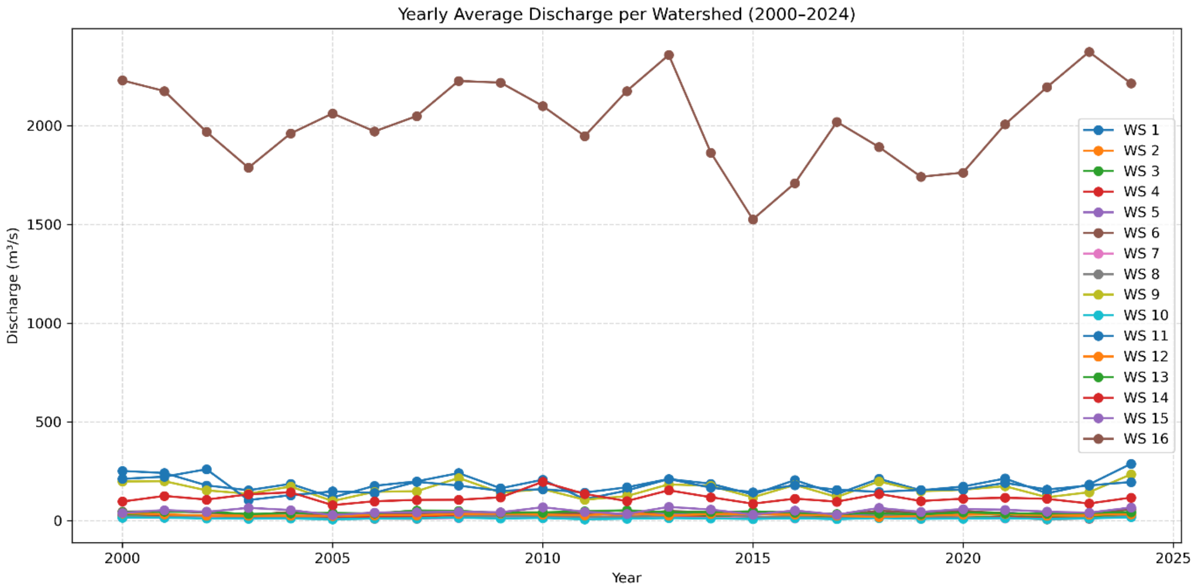


Figure 12: Yearly average inflows to the dams for per watershed for the 25-year period.

3.2.1 High-Flow Watersheds (Major Potential)

As shown in Figure 12, the watersheds exhibit a wide spectrum of discharge magnitudes, reflecting diverse catchment sizes, geographical locations, and climatic influences. Watershed 16 stands out as the largest and most dynamic, with annual average discharges consistently in the range of 1500 to 2500 m^3/s. Its peak monthly flows often exceed 3000 m^3/s, reaching an exceptional 4385.71 m^3/s in April 2013. This watershed represents significant potential for large-scale hydropower development. Watersheds 1, 9, and 11 upstream of Tuilières, Prayssac and KW Gundelsheim also show substantial inflows, with annual averages typically ranging from 150 to 300 m^3/s. These are likely major river systems with considerable hydropower capacity.

3.2.2 Medium-Flow Watersheds (Moderate Potential)

Watersheds 14, 15, and 13 generally fall into this category, with annual average discharges ranging from 80 to 150 m^3/s. Their flows are significant enough for medium-sized hydropower projects or multiple smaller installations. Watersheds 5 and 12 also exhibit moderate flows, typically averaging 30 to 50 m^3/s, with less extreme variability, making them potentially suitable for more consistent run-of-river schemes.

3.2.3 Low-Flow Watersheds

Watersheds 2, 3, 4, 8, and 10 consistently show lower average discharges, generally below 30 m^3/s. Watersheds 6 and 7 are the smallest, often recording monthly flows in single digits, with annual averages typically below 50 m^3/s. These watersheds would be best suited for small-scale, decentralized, or run-of-river hydropower projects, potentially with limited storage requirements due to their smaller volumes.

3.2.4 Dominant Seasonal Flow Regimes

During the period of March, April and May, Watersheds 1, 6, 7, 9, 11, 14, 15, and 16 consistently exhibit their highest flows due to snowmelt significantly contributing to runoff. This could be seen in figure 13. Summer Lows (July-September), Almost all watersheds experience their lowest flows during the summer months (July, August, September). This is a common feature it is driven by reduced precipitation, increased evapotranspiration, and the absence of snowmelt. The severity of summer lows varies, smaller watersheds like 6, 7, and 10 can experience extremely low flows, sometimes approaching zero, which would severely limit hydropower generation without significant upstream storage. Autumn/Winter Rises, many watersheds show a secondary increase in discharge during autumn and early winter (October, November and December), often extending into January and February. This is likely due to increased rainfall and reduced evapotranspiration in the cooler months. Watersheds 1, 8, 9, and 16 often display strong late-year increases, indicating a significant contribution from autumn precipitation. This provides a crucial second period of higher flows for hydropower generation, complementing the spring melt.

3.2.5 Notable Wet Years

Figure 13 below shows monthly time series of high discharge for selected watersheds in 2013. 2013 and 2003 stand out as wet years for several high-flow watersheds, with Watershed 16 recording its absolute peak in April 2013 (4385.71 m3/s) and another very high peak in 2023 (3288.75 m3/s).

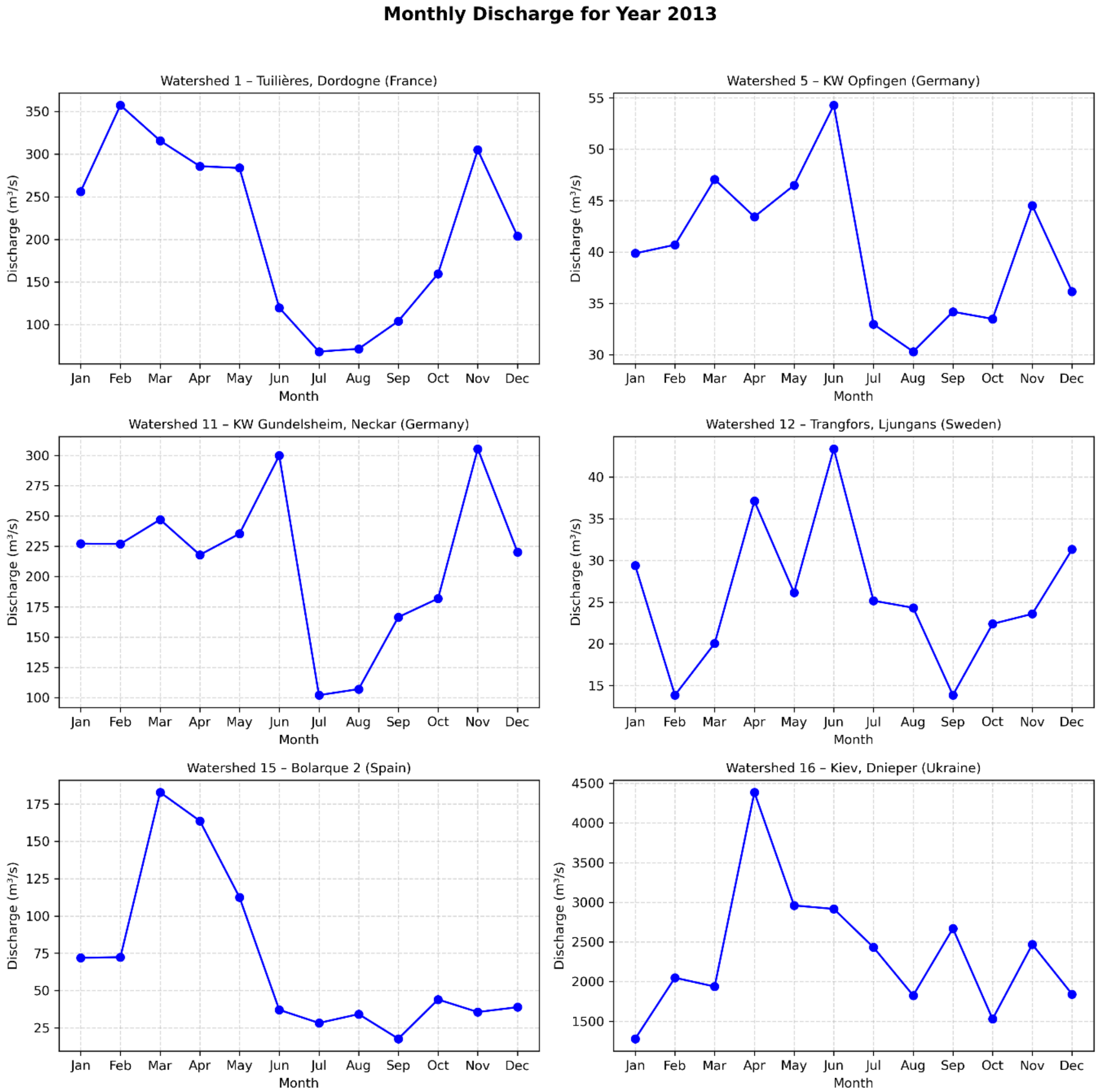


Figure 13: Monthly discharge time series for the year 2013.

3.2.6 Notable Dry Years

Figure 14 below shows monthly time series of high discharge for selected watersheds in 2003. Years like 2011 and 2015 appear to be as well, characterized by lower overall discharge and more pronounced summer lows. For instance, Watershed 10's lowest recorded monthly discharge was 0.91 m^3/s in August 2015. This poses significant challenges for continuous power generation.

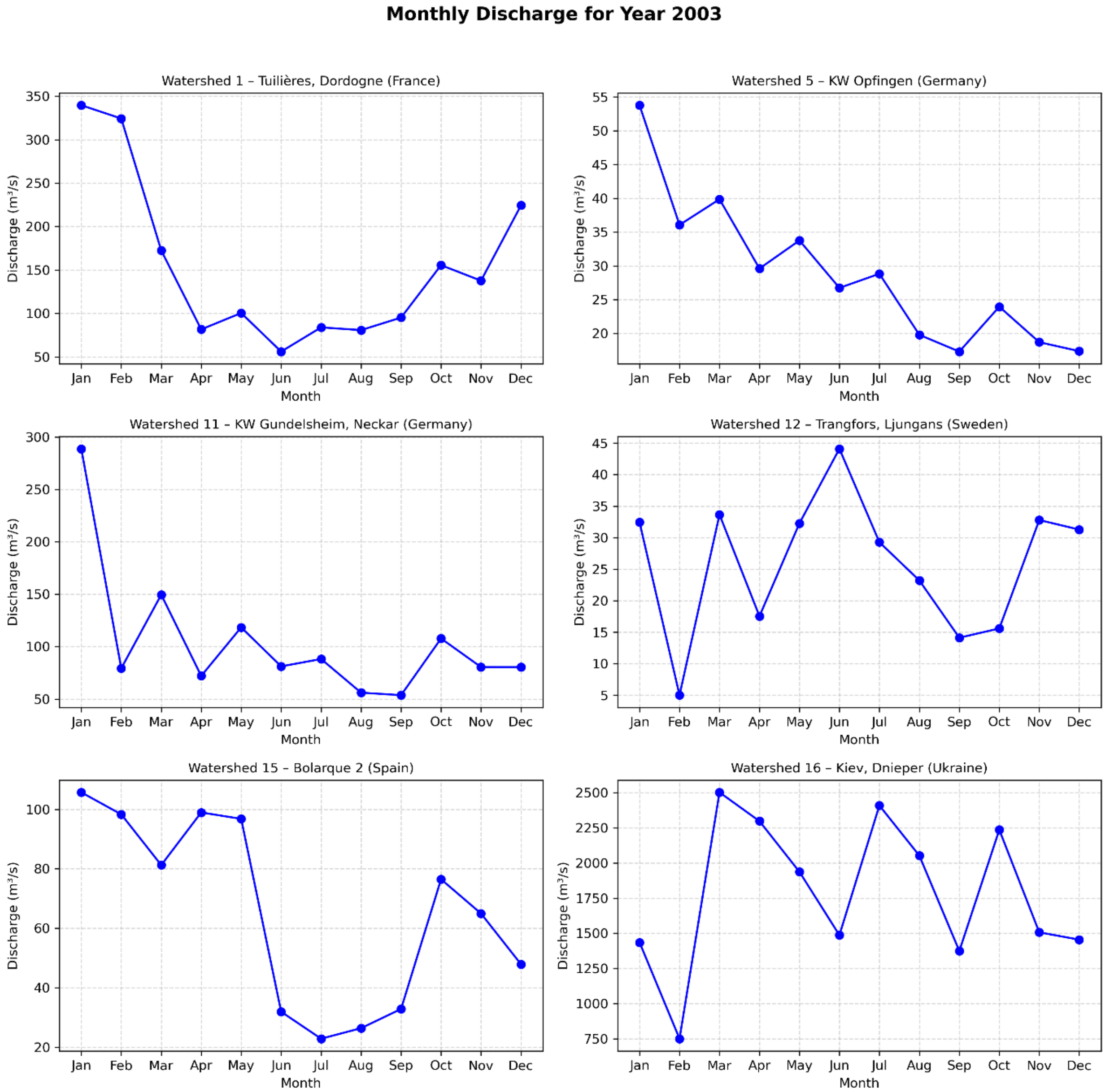


Figure 14: Monthly discharge time series for the year 2003.

3.2.7 Implications for Technical Hydropower Potential

The discharge analysis provides critical insights for evaluating the technical hydropower potential of these European catchments. The significant discharge volumes in watersheds like 16, 1, 9, and 11 confirm their high technical potential for large-scale hydropower development. The identification of extreme high and low flow events underscores the importance of designing hydropower infrastructure with resilience to both floods and droughts. This includes adequate spillway capacity for flood management and sufficient storage for drought mitigation. The diverse hydrological characteristics among the 16 watersheds emphasize that a site-specific approach to hydropower planning is essential. The optimal type and scale of hydropower development (example; large reservoir, run-of-river, pumped-storage) will vary significantly depending on the local flow regime and variability. The variability observed, particularly the summer lows, reinforces the thesis's initial motivation, hydropower's flexibility is vital to complement intermittent sources like wind and solar. During summer solar peaks, hydropower might need to reduce generation to conserve water or provide rapid ramp-up/down services. During winter, consistent high flows can provide reliable baseload or peak power.

This detailed analysis of discharge data forms a robust foundation for the subsequent steps in my thesis, particularly in calculating the actual hydropower generation and evaluating the viability of different sites. Figure 15 below shows Monthly discharge time series for all watersheds in the year 2013.

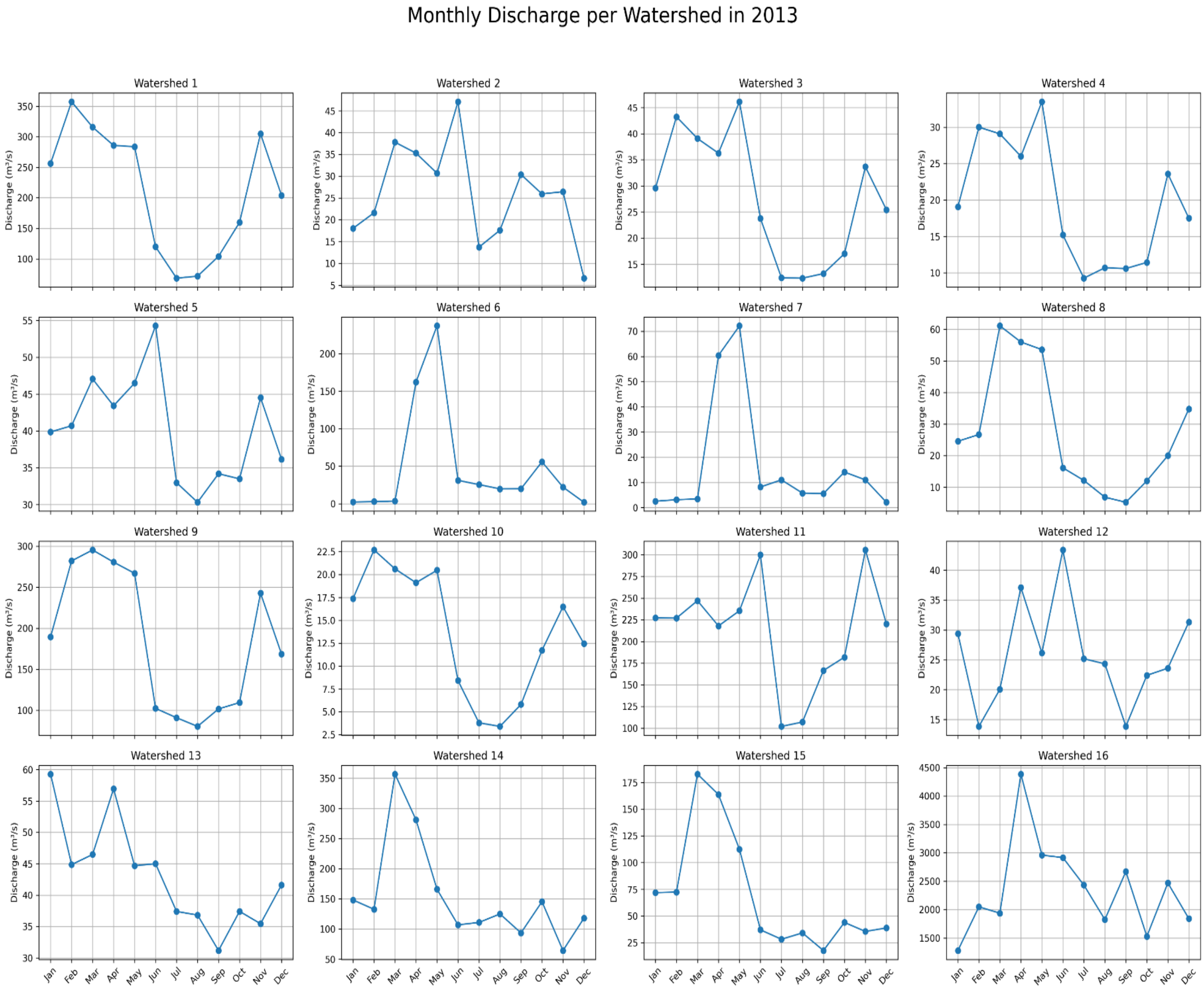


Figure 15: Monthly discharge time series for all watersheds in the year 2013

3.3 Comprehensive Analysis of Watershed Monthly Volumes (2000-2024)

This analysis delves into the monthly water volume data for 16 European mountainous watersheds over a 25-year period (2000-2024). Understanding water volume is paramount for hydropower assessment, as it directly quantifies the total available resource for energy generation and where applicable, dictates the necessary storage capacities for reliable operation. Figure 16 below shows monthly volume time series for all watersheds in the year 2013.

Figure 16: Monthly Volume time series for the year 2013.

3.3.1 High Volume Watersheds

The Kiev dam (watershed 16) consistently dominates in terms of total monthly and annual volume due to its huge upstream area. Its monthly volumes frequently exceed 5×109 m3, with peak months reaching over 1.1×1010 m^3 in April 2013). This makes it a prime candidate for large-scale, multi-purpose hydropower projects requiring substantial storage. Watersheds 1, 9, and 11 also exhibit very high volumes, typically ranging from 5×10^8 m3 to 1.5×10^9 m^3 in peak months.

3.3.2 Medium and low Volume Watersheds

Watersheds 14 and 15 show substantial monthly volumes, often in the range of 1×10^8 m^3 to 8×10^8 m^3. These catchments have sufficient water resources for medium-sized hydropower plants, potentially with smaller or multiple storage facilities. Watersheds 2, 3, 4, 8, and 10 consistently record lower monthly volumes, typically below 1×10^8 m^3. Watersheds 6 and 7 are the lowest in terms of total volume, often in the range of 1×10^6 m^3 to 2×10^8 m^3.

3.4 Comprehensive Analysis of Hydropower Generation (2000-2024)

This section provides a detailed analysis of monthly hydropower generation from 16 watersheds over a 25-year period as shown in figure 17 which describes average power per watershed from 2000 - 2024. The primary objective is to categorize watersheds based on their production characteristics and identify key statistical and temporal patterns that can inform and validate a model of hydropower potential. While the data represents a specific sample, the identified trends in seasonal and inter-annual variability are highly relevant to a broader study of European hydropower dynamics.

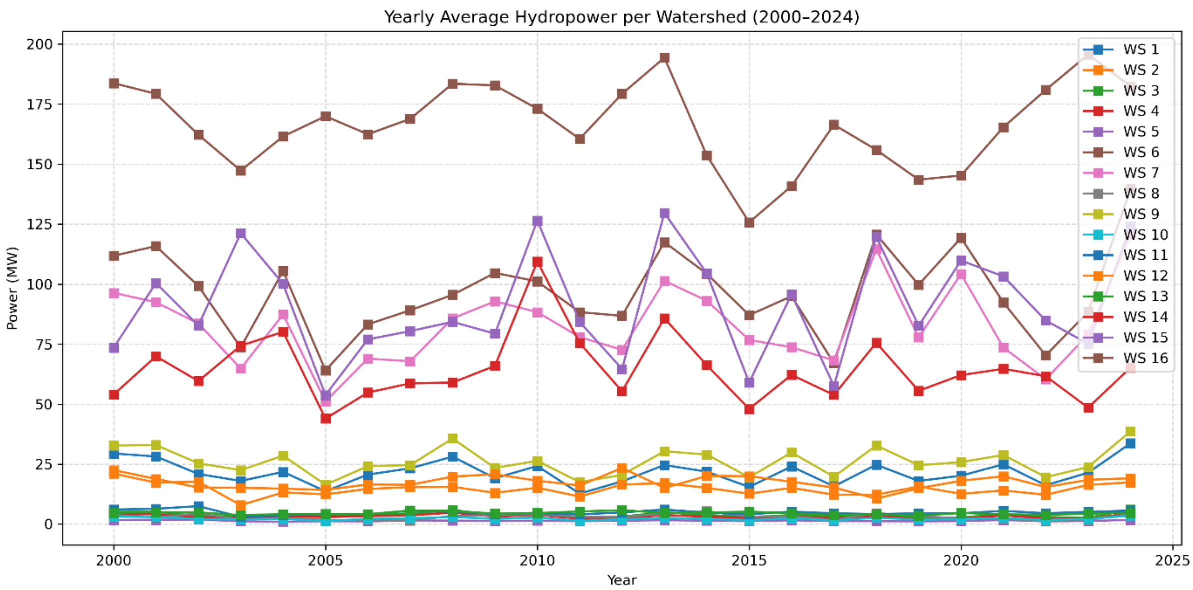


Figure 17: Average Power Per Watershed From 2000 - 2024

3.4.1 High-Potential Watersheds

As shown in figure 18 and 19, these include Watersheds 6, 7, 14, 15, and 16, they consistently demonstrate the largest hydropower potential. Their peak monthly generation frequently exceeds 200 MW and, in some cases, can surpass 700 MW. Watersheds 6 and 7 are particularly notable for their extremely high, though seasonal, peaks, with Watershed 6 reaching 585.51 MW in May 2001 and Watershed 7 reaching 493.56 MW in May 2009. Watershed 16 stands out as a consistently high producer, with monthly output often above 200 MW and a peak of 413.03 MW in April 2013.

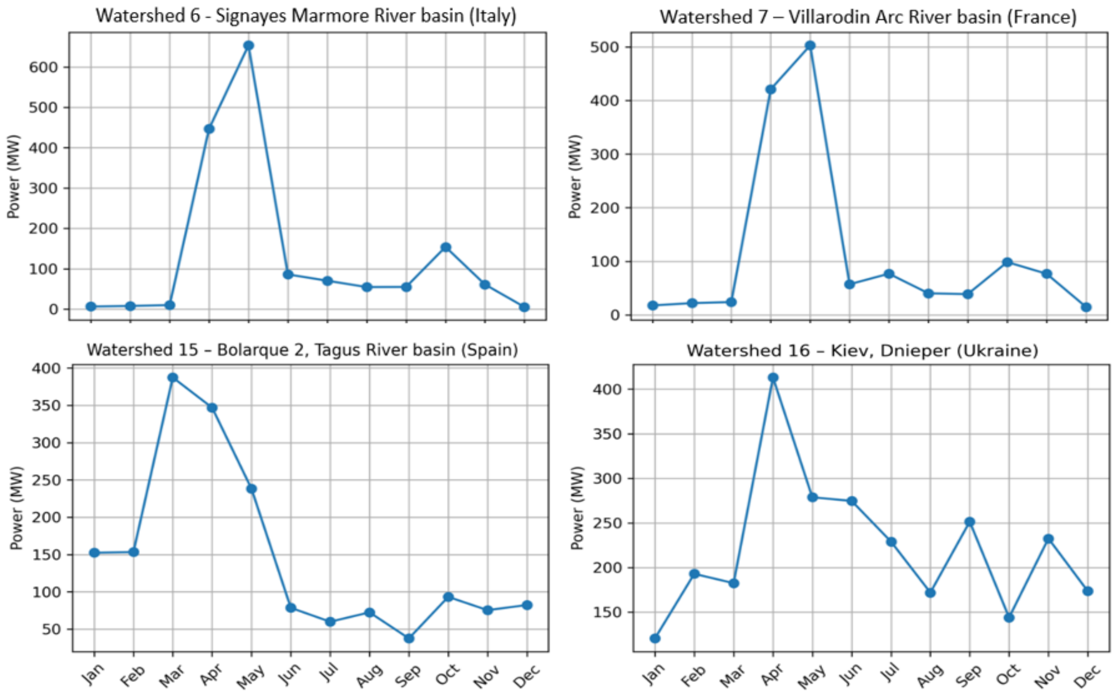


Figure 18: High potential watersheds 2013 monthly time series (MW).

3.4.2 Medium-Potential Watersheds

Watersheds 1, 9, and 12 generally fall into this category, with annual average potential ranging from 20 to 60 MW. Their power output is significant enough for medium-scale projects. Watershed 12 is distinct in this group, exhibiting a relatively stable generation profile with less extreme seasonal variability, making it potentially suitable for consistent run-of-river schemes.

Low-Potential Watersheds, the remaining watersheds, including Watersheds 2, 3, 4, 5, 8, 10, 11, and 13.

3.4.3 Dominant Seasonal Power Regimes

The analysis reveals distinct seasonal patterns in hydropower potential, indicative of a strong link to hydrological regimes, particularly in mountainous regions. The most prominent feature for many watersheds, especially those with high potential, is a pronounced generation peak during the months of March, April, and May. This strong peak is a characteristic of catchments where snowmelt significantly contributes to increased river flow, thereby maximizing turbine output. For example, Watershed 15 consistently records its highest generation during this period, with a peak of 387.28 MW in March 2013. This pattern suggests that hydropower generation in these systems is naturally at its highest in spring, requiring robust management strategies to utilize this peak output effectively. Almost all watersheds experience a significant drop in power potential during the summer months. This is a common feature driven by reduced precipitation and increased evapotranspiration.

3.4.4 Notable High-Potential watersheds in 2024

Figure 19 shows that 2024 stand out as particularly high-potential years for several watersheds, such as 1, 9 and 16 as shown below. This year represent ideal conditions for hydropower generation, but also pose risks related to managing excess water flow and flood control.

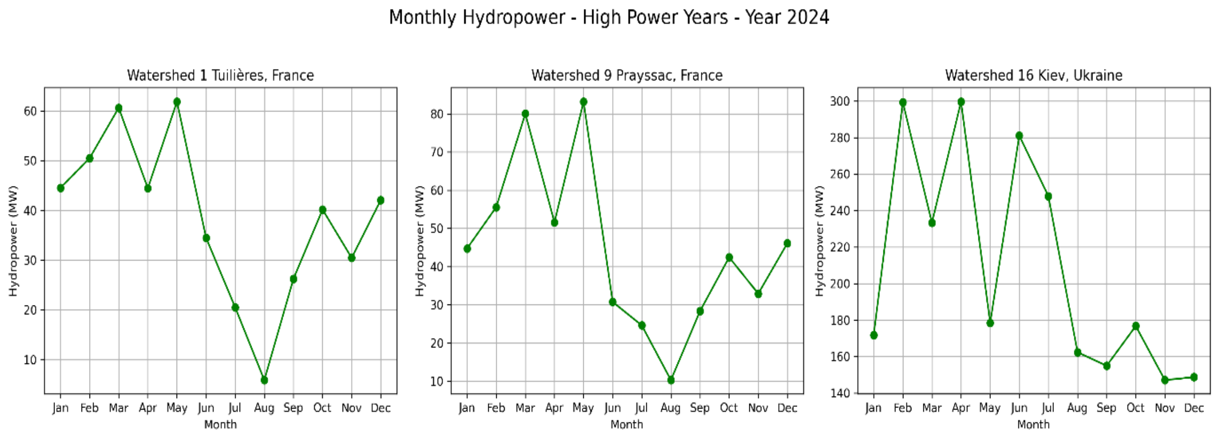


Figure 19: High Potential year (2024)

3.4.5 Notable Low-Potential watersheds in 2003

The years 2003 and 2015 appear to be drier years across many watersheds, Figure 20 below shows watersheds 1, 9and 16 characterized by lower overall potential as in watershed 1and 9 recording below 10MW in June 2003. For example, Watershed 10's lowest recorded monthly potential was 0.2 MW in August 2015. Such periods pose significant challenges for continuous power generation.

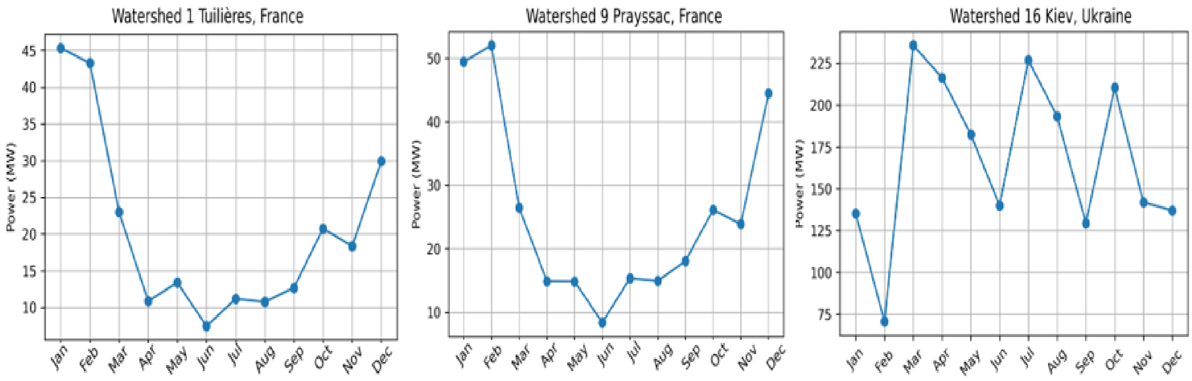


Figure 20: Low Potential year (2003)

3.4.6 Summary of Hydropower Potential Estimation

The analysis of the calculated hydropower potential against the actual installed capacity shows a mixed outcome. While some values are a very close match (within 30% difference), a significant number of the calculated values are very far off, with many being more than 60% different from the real data. The main reason for these large discrepancies is likely that the calculation model is too simple. It probably doesn't account for crucial real-world factors like a dam's technological efficiency, fluctuating river discharge rates, and operational limitations.

The rationale of this thesis is to develop a methodology to predict hydropower potential. This is achieved by calculating the hydropower potential and then compare the results with the actual installed capacity of the power plants.

The model tends to provide a good estimate of the general magnitude of hydropower potential. In some cases, the calculated potential is very close to the installed capacity, indicating a well-matched system. For example, Catchment 2 (Kraftwerk Alberschwende) has an installed capacity of 30 MW and a calculated potential of 16.68 MW, which is a reasonable and defensible result considering operational factors that may hinder the technical potential estimation.

Table 4: calculated hydropower potential against the actual installed capacity

Watershed	Dam Name	Country	Head (m)	Observed Power (MW)	Calculated Power (MW)	Accuracy of estimated or calculated power
1	Tuilières	France	17	32	24.65	Green
2	Kraftwerk Alberschwende	Austria	96	30	16.68	Green
3	Teillet-Argenty	France	26	5.5	4.47	Green
4	Saint-Gervais-d'Auvergne	France	28	8.8	3.63	Yellow
5	KW Öpfingen	Germany	6	3	1.63	Green
6	Signayes	Italy	351	42	110.63	Red
7	Villarodin	France	888	357	94.78	Red
8	Farigliano	Italy	23	5	3.47	Green
9	Prayssac	France	24	4.7	29.88	Red
10	Voutezac	France	28	2.82	2.63	Green
11	KW Gundelsheim	Germany	4.2	3.05	5.62	Red
12	Trangfors	Sweden	85	73	19.98	Red
13	Motala	Sweden	16	14	5.27	Red
14	CIJARA 1	Spain	81	102	73.6	Green
15	Bolarque 2	Spain	270	240.4	103.95	Yellow
16	Kiev	Ukraine	11.8	440	190.34	Yellow

Green - Good Estimation	Green (≤ 50% deviation)
Yellow - Fair Estimation	Yellow (50–60% deviation)
Red - Poor Estimation	Red (> 60% deviation)

3.5 Analysis of the Discharge-Hydropower Relationship

The theoretical link between river discharge and hydropower generation suggest that the amount of electrical energy produced is directly proportional to the volume of water flowing through the turbines. The analysis in figure 22 confirmed a strong, positive, and statistically significant relationship between annual average discharge and annual hydropower generation, this is strongly manifested by the year 2024, where the power generated shoots up in many watersheds. It is observed that the more discharge increases the more power produced.

In some cases, higher discharge doesn't always translate to higher power because reservoir water head contributes to a higher power as in the case of dam 6, Signayes, in Italy which has a very small discharge value but due to its high head, it produces high power. This can be seen in other cases in figure 23 below.

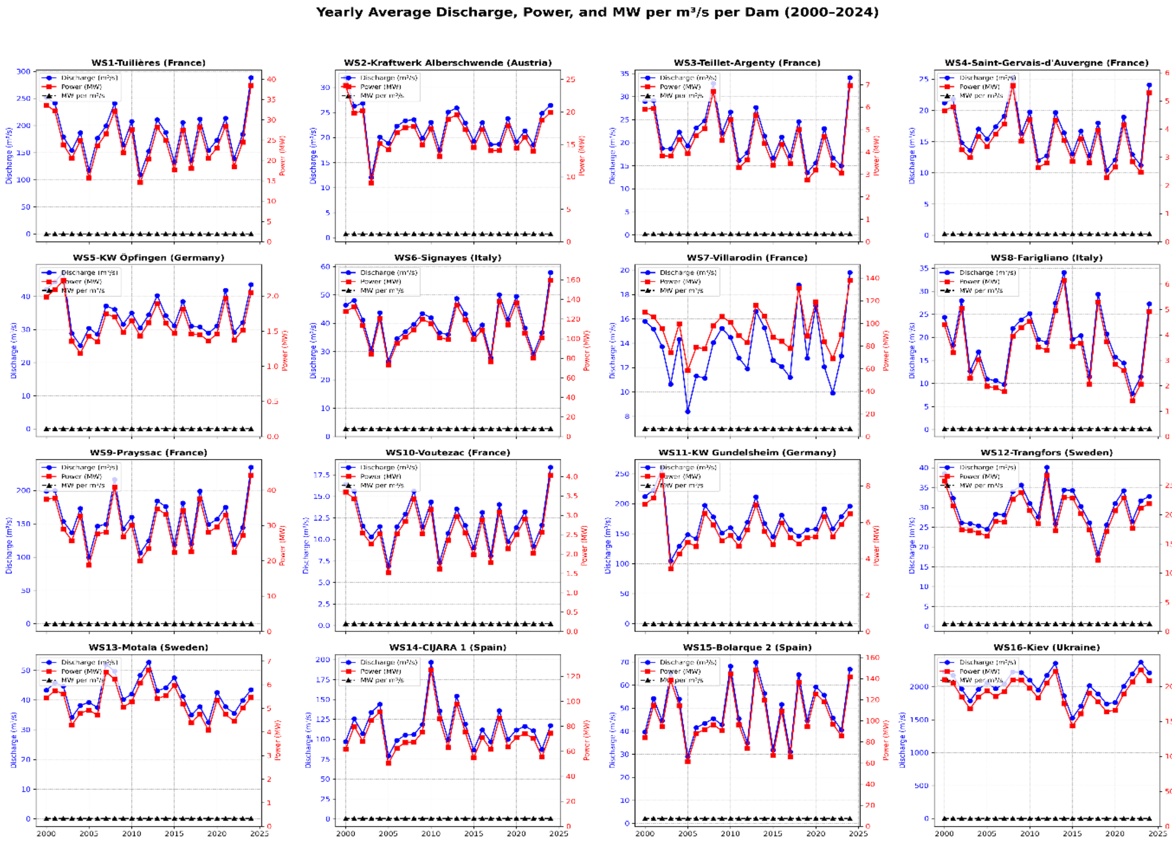


Figure 21: Discharge vs Hydropower

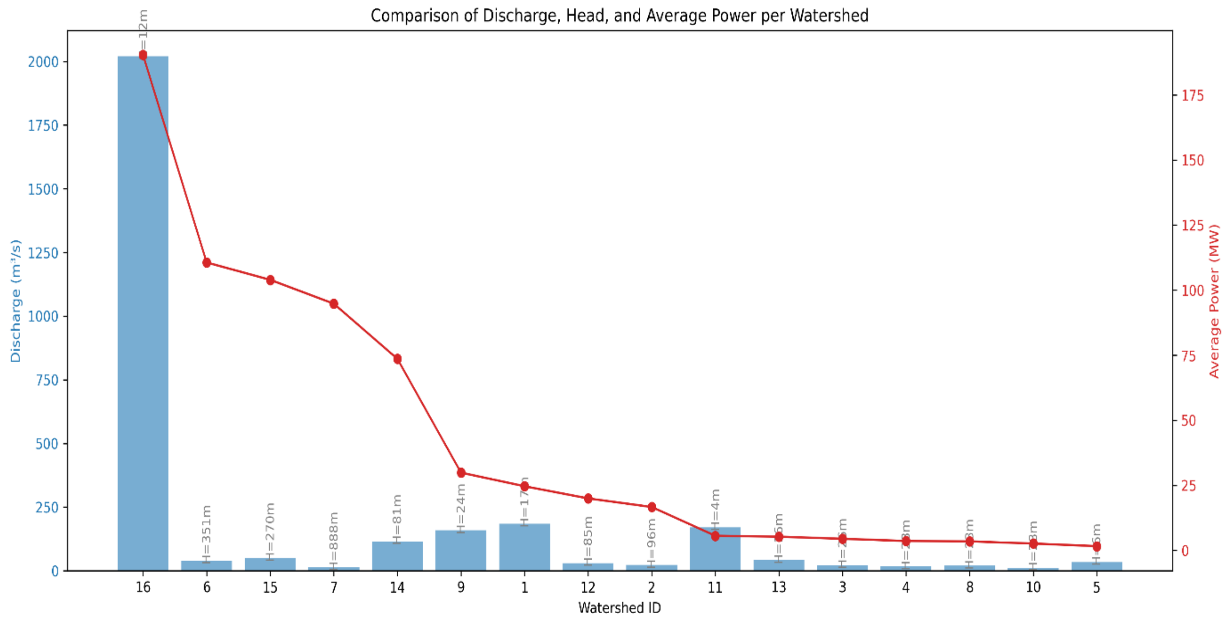


Figure 22: Discharge, average Power and head.

A direct visual inspection of the time series data confirms a near-synchronous response between the two variables. High-discharge years consistently correspond to high-power years, and vice versa. The year 2024 stands out as a high-flow year for many catchments, resulting in a corresponding peak in hydropower generation. In contrast, years such as 2003 and 2019 were marked by lower discharge volumes, which directly translated to a reduction in energy output across the region. This highlights the sensitivity of hydropower systems to short-term fluctuations in water availability.

3.5.1 Implications for Future Modelling

The validation process reveals that while the model successfully captures the spatial characteristics and provides a good first-order approximation of hydropower potential, it requires refinement to improve its accuracy. Future model iterations should focus on incorporating a more nuanced representation of hydrological processes and, crucially, include additional parameters related to plant infrastructure and operational strategies. This could involve integrating data on dam height, turbine type, and reservoir storage capacity. Such enhancements would help to bridge the gap between the model's theoretical calculations and the empirical reality of installed capacity and observed power output, making the model a more powerful tool for future resource management and planning. The relationship between catchment size and power output is therefore non-linear. Large catchments can have diluted power potential if the terrain is flat or water is spread across many tributaries, reducing the flow concentration at the dam. Conversely, smaller catchments located in high-altitude regions with steep slopes can generate significant amounts of power because water drops from higher elevations, increasing potential energy.

Patrial Conclusion

In summary, catchment size for each dam was well calculated with all 16 watersheds reaching very close. This explains why two watersheds with similar catchment areas can have very different power outputs. The model consistently either overestimates or underestimates the installed capacity in other catchments. The most extreme case of overestimation is seen in Catchment 6 (Signayes), where the model calculates a potential of 110.63 MW despite an installed capacity of just 42 MW. Catchment15, Bolarque, has calculated potential of 103.95 MW against a capacity of 240.4 MW. The model's results likely represent the theoretical maximum potential, whereas installed capacity is a function of complex engineering, economic, and operational decisions, this may include more factors that the model doesn’t consider. The significant overestimation in certain catchments could be as a result of the model's inability to account for these specific engineering constraints and operational limitations.

GENERAL CONCLUSION AND PERSPECTIVES

GENERAL CONCLUSION AND PERSPECTIVES

The goal of this thesis was to develop and validate a model for assessing hydropower potential across Europe. Comparison of the calculated catchment areas shows a strong correlation and confirms the accuracy of the methodology. By analysing a comprehensive dataset of discharge and hydropower generation from sixteen dams. The primary validation of this model was conducted by comparing its simulated hydropower output against the observed monthly hydropower generation data from 2000 to 2024. The model accurately reproduced the key trends and seasonal cycles observed in the empirical data.

The results of this study are consistent with findings in established literature on hydropower potential modelling. For instance, the observed strong correlation between discharge and power generation aligns with previous studies that identify river flow as the dominant factor for energy production (Obahoundje & Diedhiou, 2022).

The central finding of my work is the strong positive relationship between river discharge and hydropower generation. My analysis showed that as discharge increases, so does power output, But it wasn't always a perfect match similar to findings from Ak et al., (2017) who also confirmed findings such as the seasonal decoupling of discharge and power output. I observed that peak discharge in the spring, often due to snowmelt, does not always directly lead to peak power generation. Furthermore, my model's validation against observed data from the table showed mixed results. While the model successfully replicated the physical catchment area, it demonstrated notable discrepancies in estimating discharge and hydropower potential in certain cases. This confirms that while the model provides a strong first-order approximation, it requires refinement. It could be assumed that the decoupling between river discharge and power generation is related to filling of reservoirs.

Contributions of the Work

The research makes several key contributions to the field of hydropower modelling. It has provided data-driven validation of the discharge-power relationship using a large and diverse set of European catchments. Hydropower potential was also estimated, which accurately captures the key hydrological drivers of energy production. Beyond just hydrology, this work highlighted the critical influence of operational factors like reservoir management and maintenance on the final power output, a finding that is essential for real-world applications. I used data to prove that the fundamental idea behind hydropower that more water means more power is true provided all other conditions remain fulfilled. This built a basic starting point for others to build on. My most important contribution might be showing that we can't just use water flow data alone. Inputs like DEM and GloHydroRes datasets are essential.

Limitations

The limitations observed in this research is the reliance solely on hydrological data. As the results showed, local operational policies can cause significant differences between the model's theoretical output and the observed installed capacity. The model also did not explicitly account for operational factors and seasonal or planned maintenance, which may cause in accuracies while trying to calculate the installed power. The data resolution (3km) is also a contributing factor to the accuracy of the results.

Future Research Recommendations

Based on the observed behaviour of the results obtained, the following recommendations could be beneficial for future research.

Climate Change Scenarios, the model could be adapted to run with future climate projections to assess how changes in precipitation and temperature might impact discharge patterns and, consequently, hydropower potential across Europe. Important to explore advanced Modelling Techniques and methods like machine learning could help to better capture the complex, non-linear relationships between a wider range of variables and hydropower output. Finally, Integration of economic factors to move from a potential-based model to a more comprehensive tool for resource managers.

BIBLIOGRAPHIC REFERENCES

Ak, M., Kentel, E., & Savasaneril, S. (2017). Operating policies for energy generation and revenue management in single-reservoir hydropower systems. *Renewable and Sustainable Energy Reviews*, *78*, 1253–1261. https://doi.org/https://doi.org/10.1016/j.rser.2017.04.067

Baird, I. G., Ziegler, A. D., Fearnside, P. M., Pineda, A., Sasges, G., Strube, J., Thomas, K. A., Schmutz, S., Greimel, F., & Hayes, D. S. (2024). Ruin-of-the-rivers? A global review of run-of-the-river dams. *Environmental Management*, *February 2025*. https://doi.org/10.1007/s00267-024-02062-5

European Commission, Joint Research Centre, Quaranta, E., Georgakaki, A., Letout, S., Mountraki, A., Ince, E. and Gea Bermudez, J., C. (2024). *Clean Energy Technology Observatory: Hydropower and Pumped Storage Hydropower in the European Union - 2024 Status Report on Technology Development, Trends, Value Chains and Markets, Publications Office of the European Union, Luxembourg, 2024*. https://doi.org/10.2760/8354439

Gøtske, E. K., & Victoria, M. (2021). Future operation of hydropower in Europe under high renewable penetration and climate change. *IScience*, *24*(9), 13–17. https://doi.org/10.1016/j.isci.2021.102999

Kouadio, C. A., Kouassi, K. L., Diedhiou, A., Obahoundje, S., Amoussou, E., Kamagate, B., Paturel, J. E., Coulibaly, T. J. H., Coulibaly, H. S. J. P., Didi, R. S., & Savane, I. (2022). Assessing the Hydropower Potential Using Hydrological Models and Geospatial Tools in the White Bandama Watershed (Côte d'Ivoire, West Africa). *Frontiers in Water*, *4*(March), 1–14. https://doi.org/10.3389/frwa.2022.844934

Lawrence, D. M., Fisher, R. A., Koven, C. D., Oleson, K. W., Swenson, S. C., Bonan, G., Collier, N., Ghimire, B., van Kampenhout, L., Kennedy, D., Kluzek, E., Lawrence, P. J., Li, F., Li, H., Lombardozzi, D., Riley, W. J., Sacks, W. J., Shi, M., Vertenstein, M., … Zeng, X. (2019). The Community Land Model Version 5: Description of New Features, Benchmarking, and Impact of Forcing Uncertainty. *Journal of Advances in Modeling Earth Systems*, *11*(12), 4245–4287. https://doi.org/10.1029/2018MS001583

Lehner, B., Czisch, G., & Vassolo, S. (2005). The impact of global change on the hydropower potential of Europe: A model-based analysis. *Energy Policy*, *33*(7), 839–855. https://doi.org/10.1016/j.enpol.2003.10.018

Manzano-Agugliaro, F., Taher, M., Zapata-Sierra, A., Juaidi, A., & Montoya, F. G. (2017). An overview of research and energy evolution for small hydropower in Europe. *Renewable and Sustainable Energy Reviews*, *75*(May 2015), 476–489. https://doi.org/10.1016/j.rser.2016.11.013

Multi-Error-Removed Improved-Terrain DEM. (n.d.). Retrieved June 17, 2025, from https://hydro.iis.u-tokyo.ac.jp/~yamadai/MERIT_DEM/%0A

Ng, J. Y., Turner, S. W. D., & Galelli, S. (2017). Influence of El Niño Southern Oscillation on global hydropower production. *Environmental Research Letters*, *12*(3). https://doi.org/10.1088/1748-9326/aa5ef8

Obahoundje, S., & Diedhiou, A. (2022). Potential impacts of climate, land use and land cover changes on hydropower generation in West Africa: A review. *Environmental Research Letters*, *17*(4). https://doi.org/10.1088/1748-9326/ac5b3b

Paprotny, D., & Morales-Nápoles, O. (2017). Estimating extreme river discharges in Europe through a Bayesian network. *Hydrology and Earth System Sciences*, *21*(6), 2615–2636. https://doi.org/10.5194/hess-21-2615-2017

Sammartano, V., Liuzzo, L., & Freni, G. (2019). Identification of potential locations for run-of-river hydropower plants using a GIS-based procedure. *Energies*, *12*(18), 1–20. https://doi.org/10.3390/en12183446

Shah, J., Hu, J., Edelenbosch, O. Y., & van Vliet, M. T. H. (2025). Global dataset combining open-source hydropower plant and reservoir data. *Scientific Data*, *12*(1), 646. https://doi.org/10.1038/s41597-025-04975-0

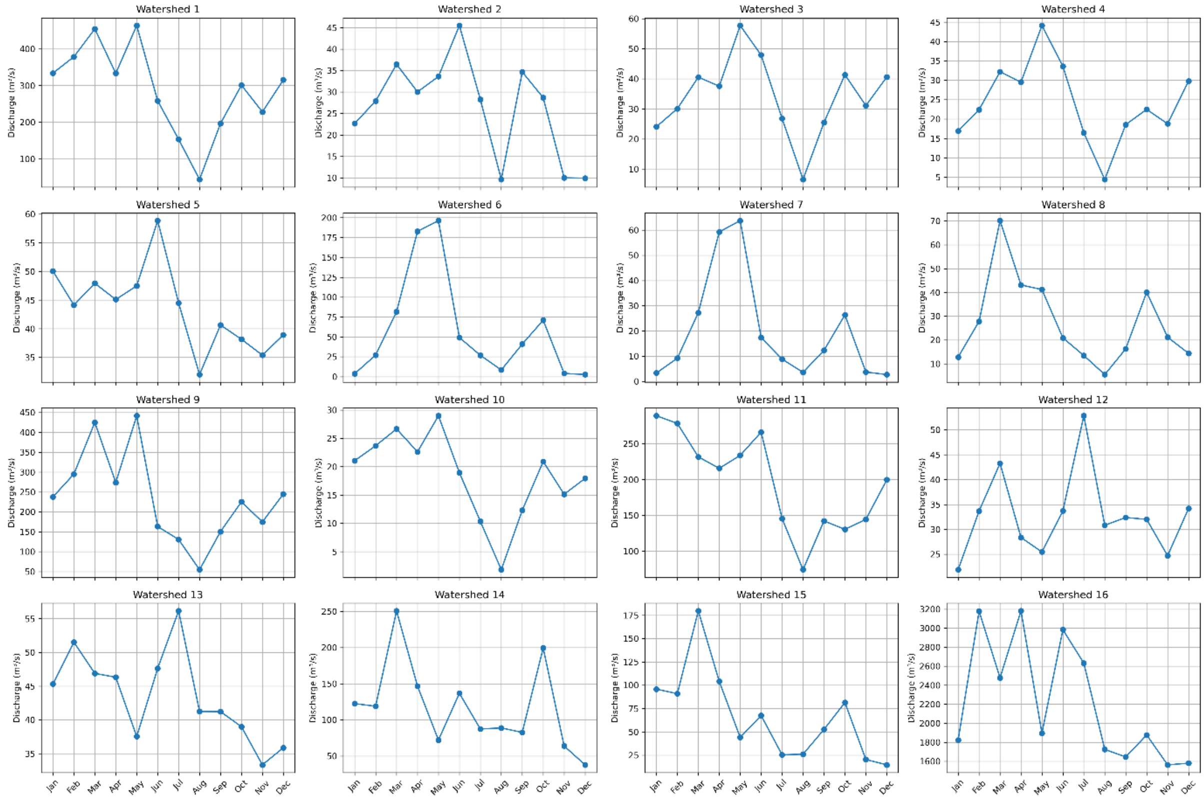
Turner, S. W. D., & Voisin, N. (2022). Simulation of hydropower at subcontinental to global scales: A state-of-the-art review. *Environmental Research Letters*, *17*(2). https://doi.org/10.1088/1748-9326/ac4e38

Wagner, B., Hauer, C., & Habersack, H. (2019). Current hydropower developments in Europe. *Current Opinion in Environmental Sustainability*, *37*(i), 41–49. https://doi.org/10.1016/j.cosust.2019.06.002

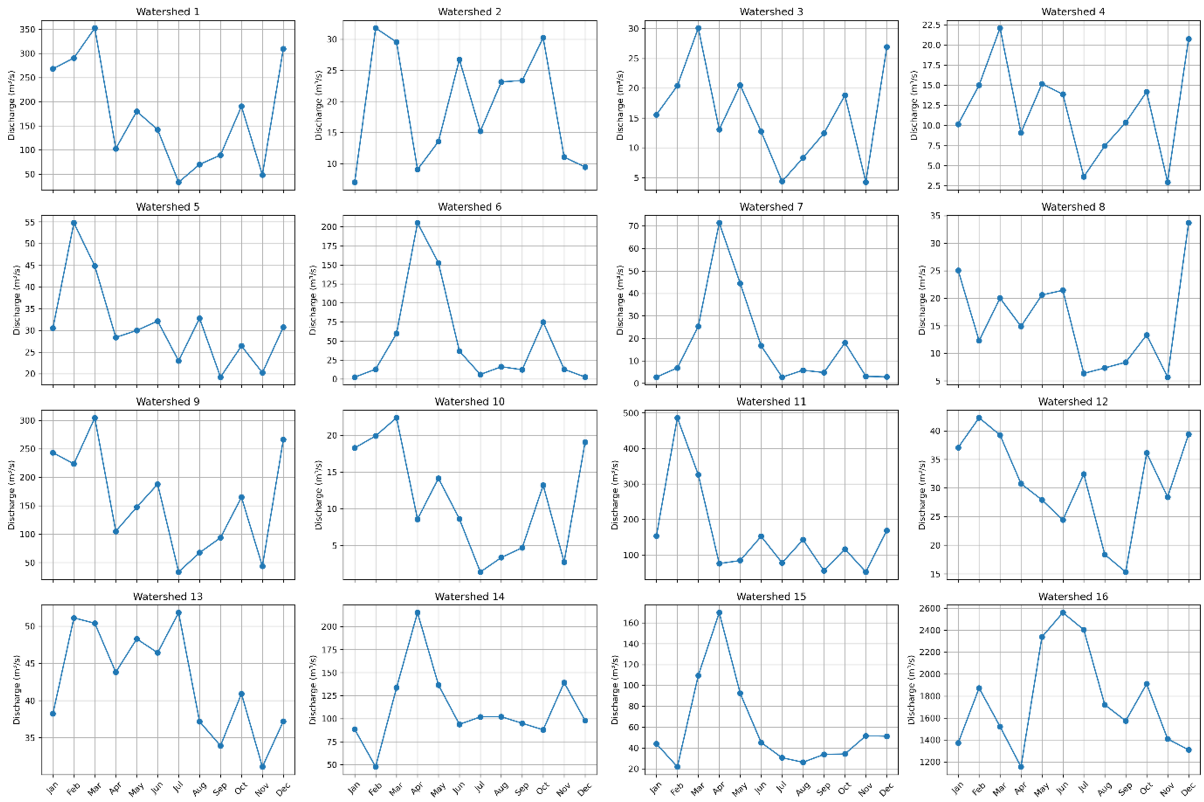
Wrzesiński, D. (2013). Uncertainty of flow regime characteristics of rivers in europe. *Quaestiones Geographicae*, *32*(1), 43–53. https://doi.org/10.2478/quageo-2013-0006

Appendix A: Hydropower monthly time series (2000 – 2024)

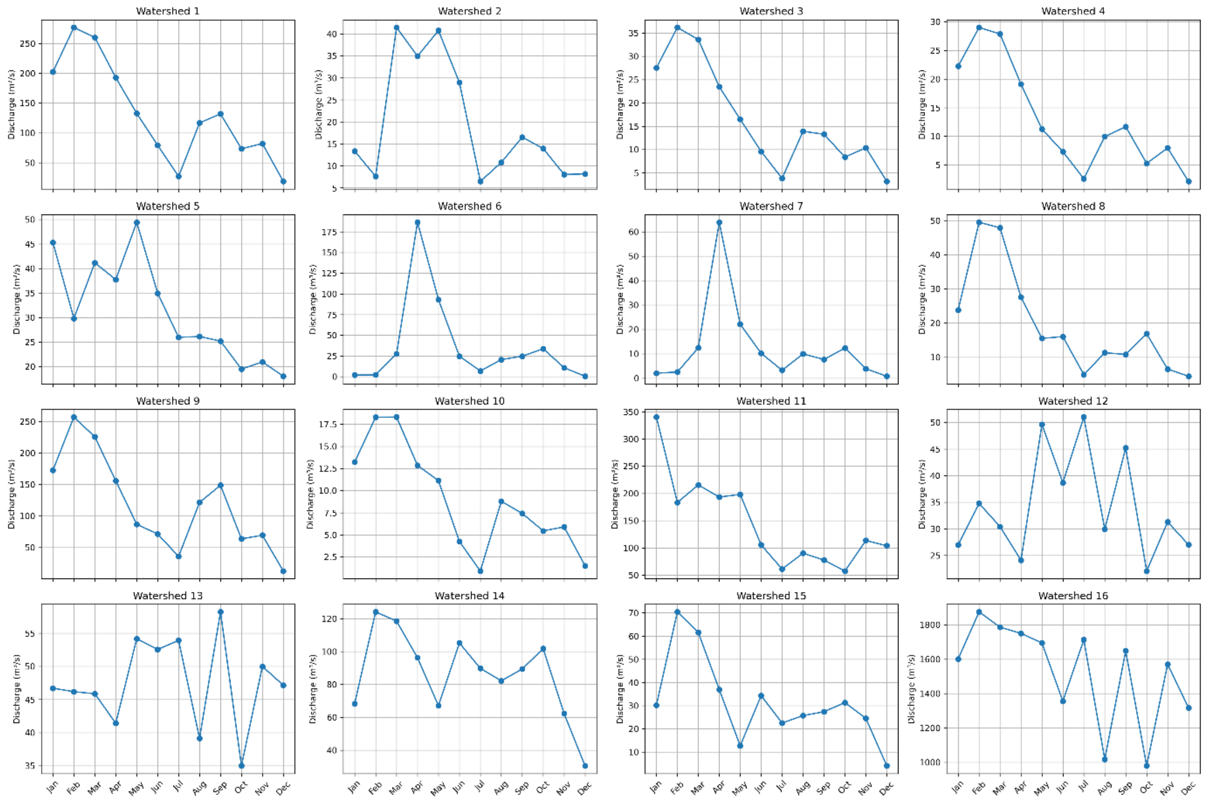
Monthly Discharge per Watershed in 2024



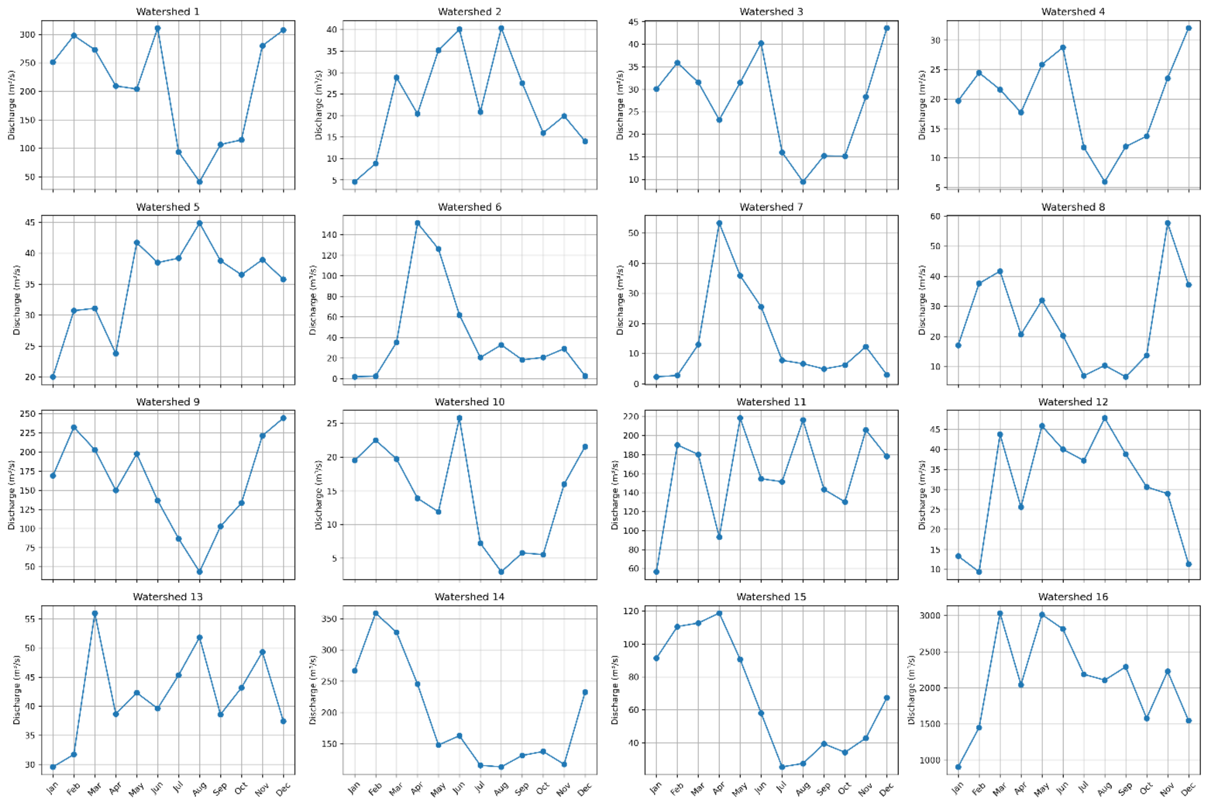
Monthly Discharge per Watershed in 2020



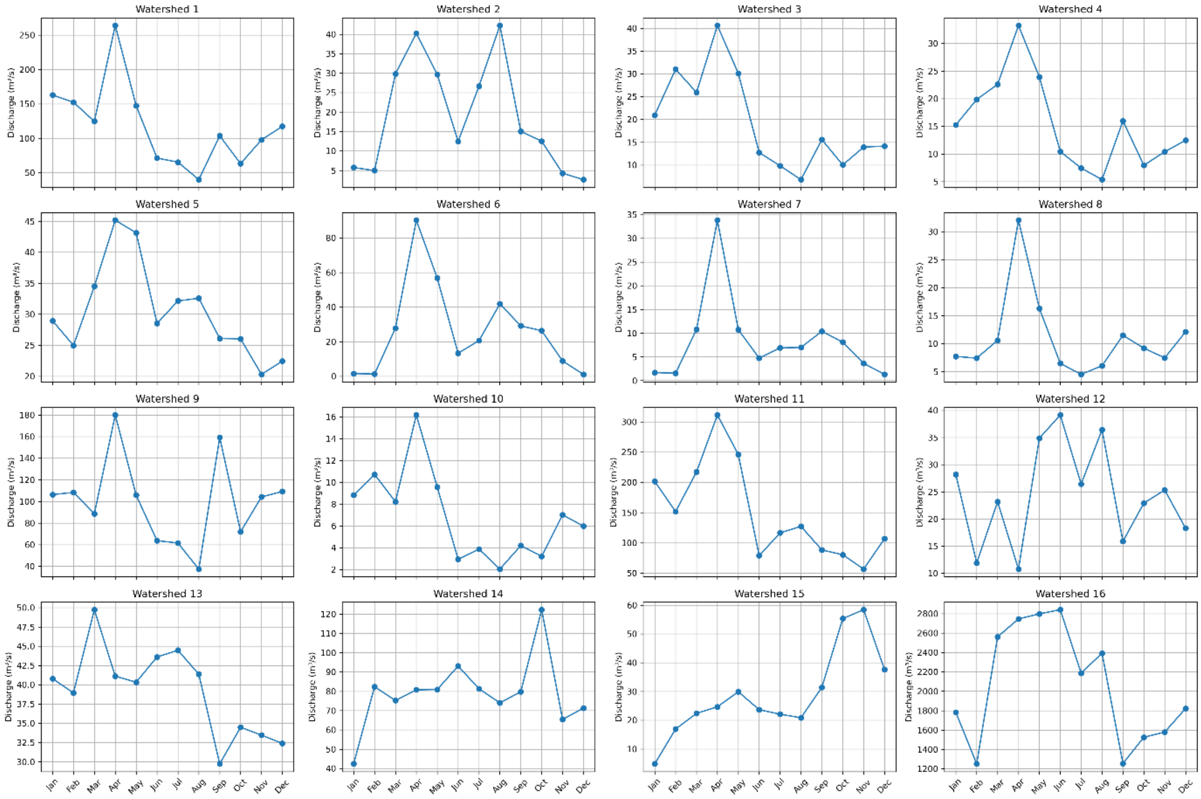
Monthly Discharge per Watershed in 2015



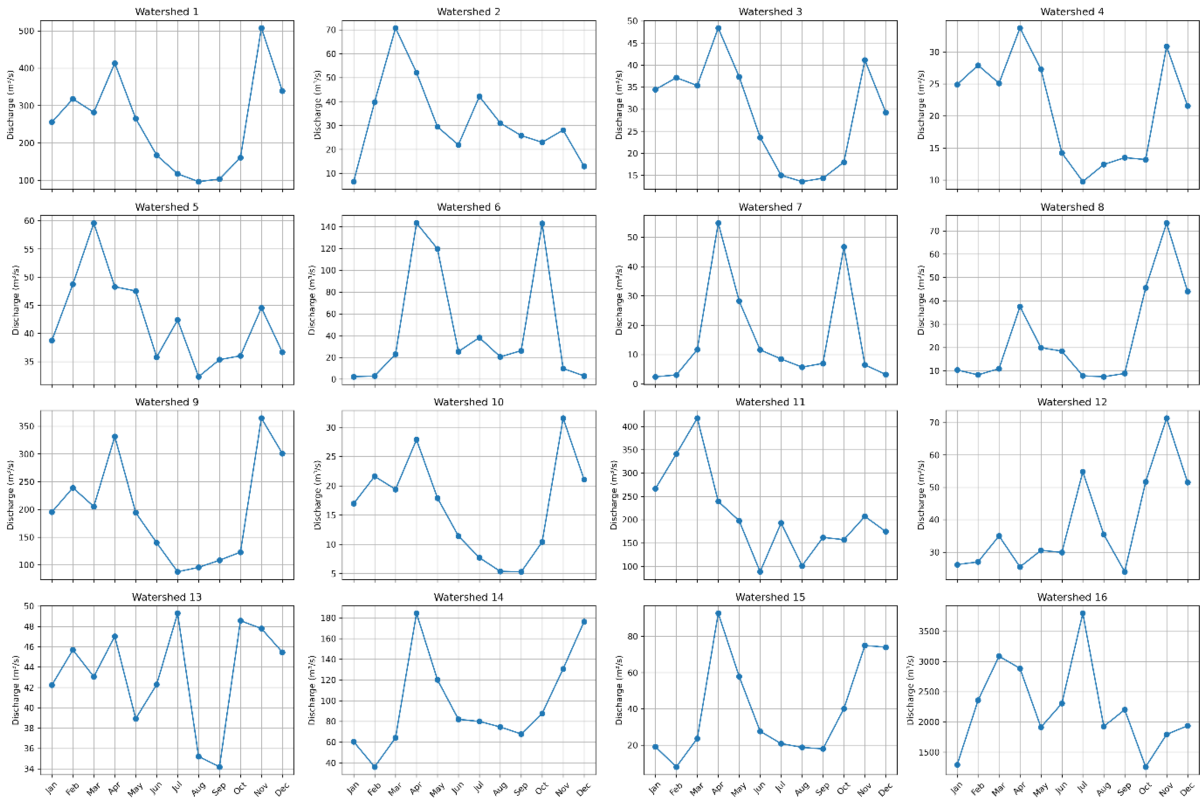
Monthly Discharge per Watershed in 2010



Monthly Discharge per Watershed in 2005

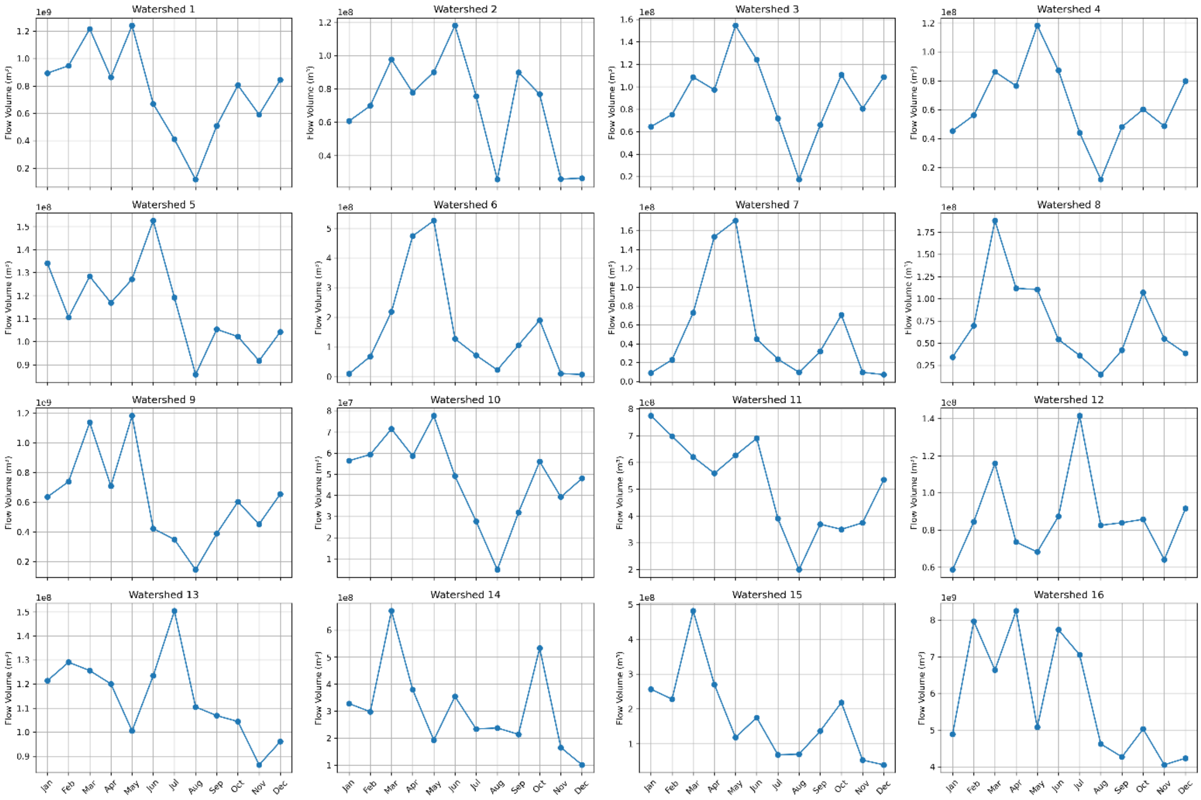


Monthly Discharge per Watershed in 2000

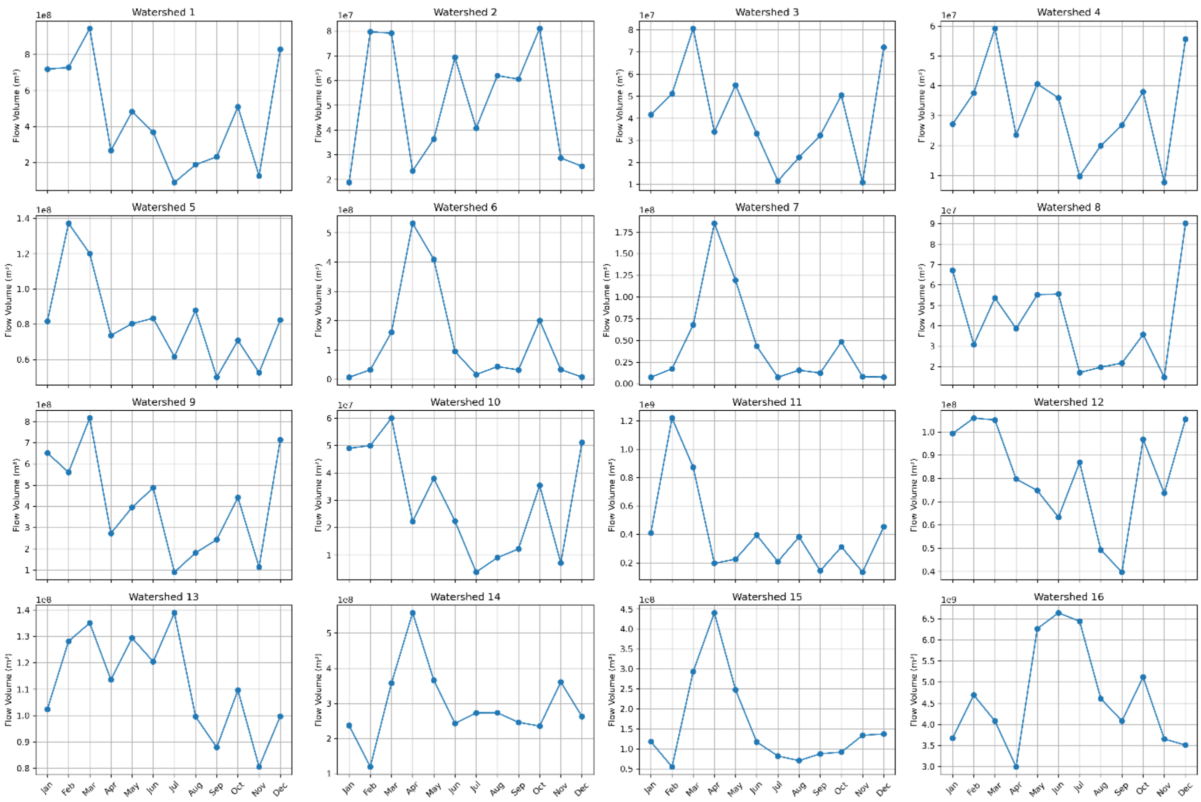


Appendix B: Flow volume monthly time series (2000 – 2024)

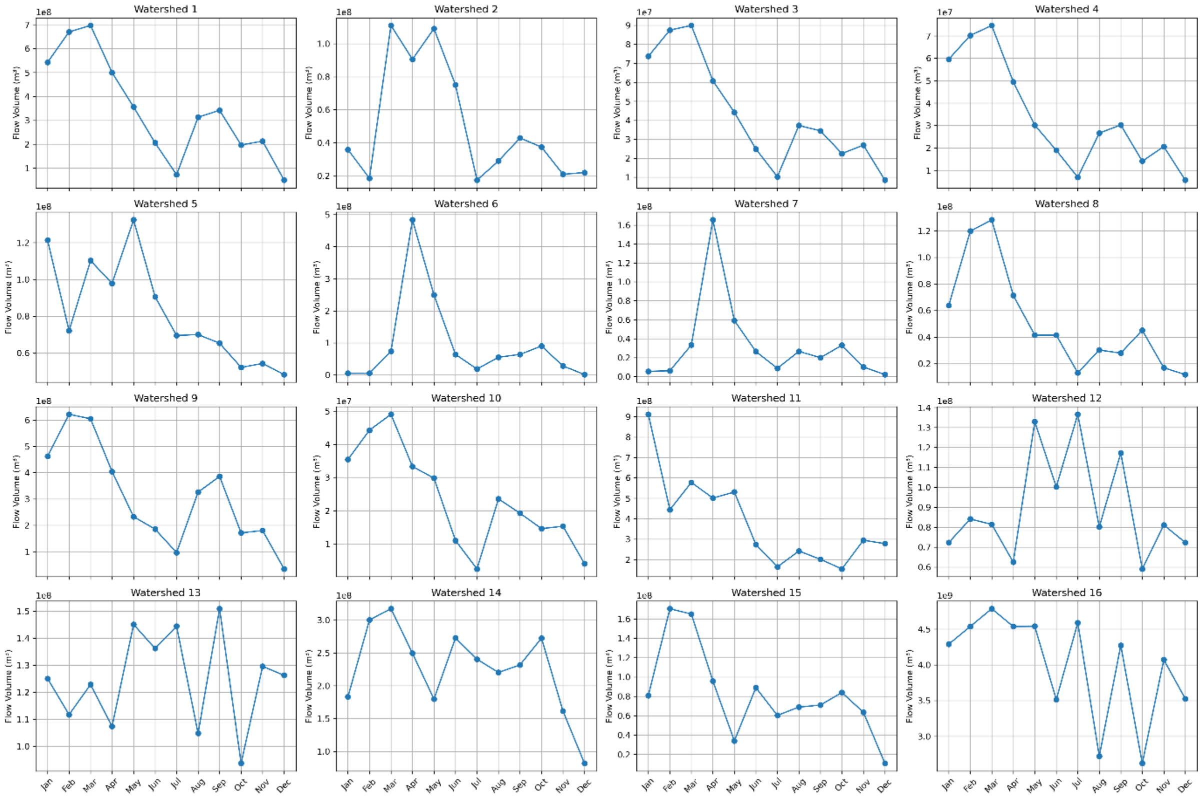
Monthly Flow Volume per Watershed in 2024



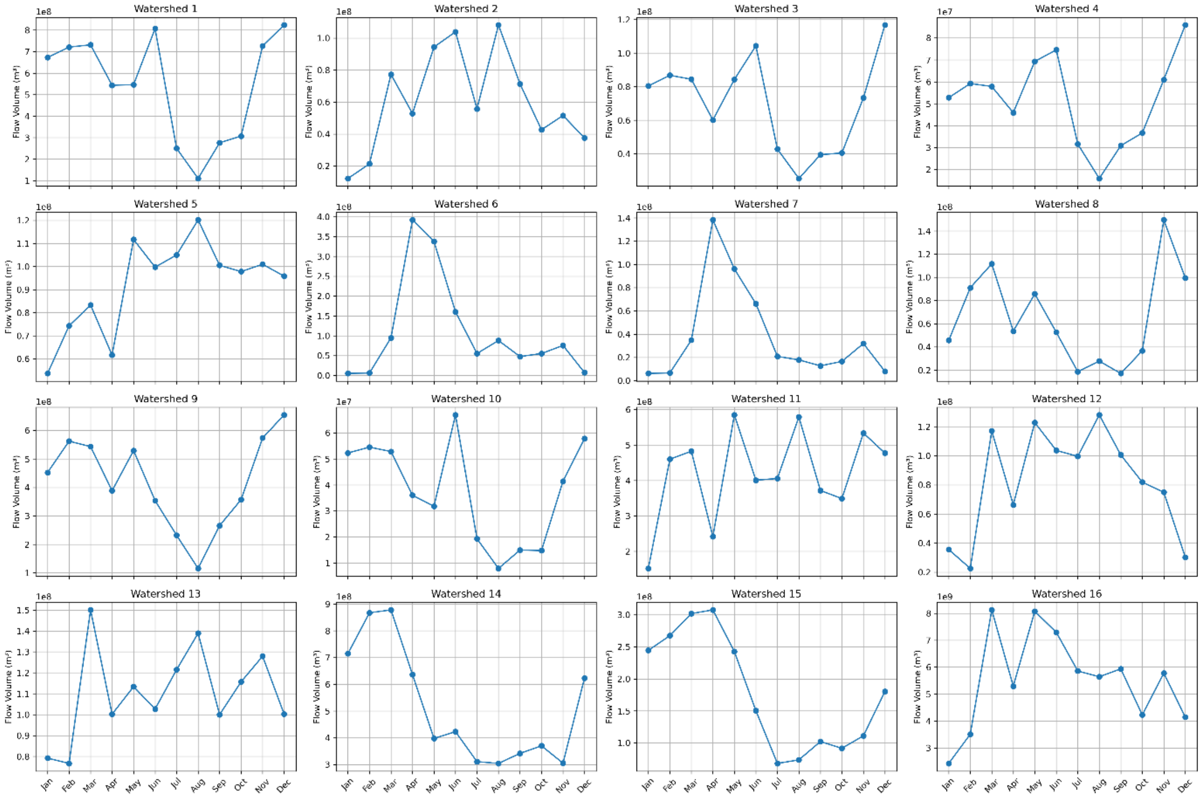
Monthly Flow Volume per Watershed in 2020



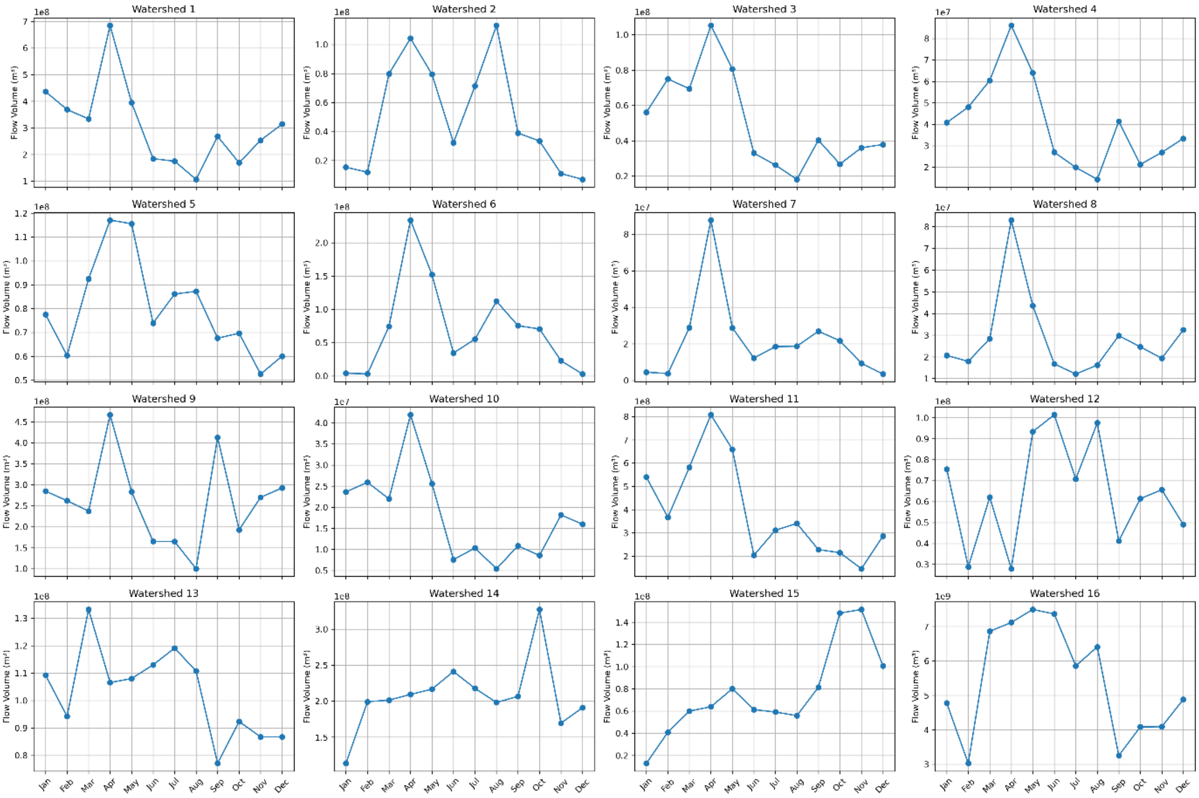
Monthly Flow Volume per Watershed in 2015



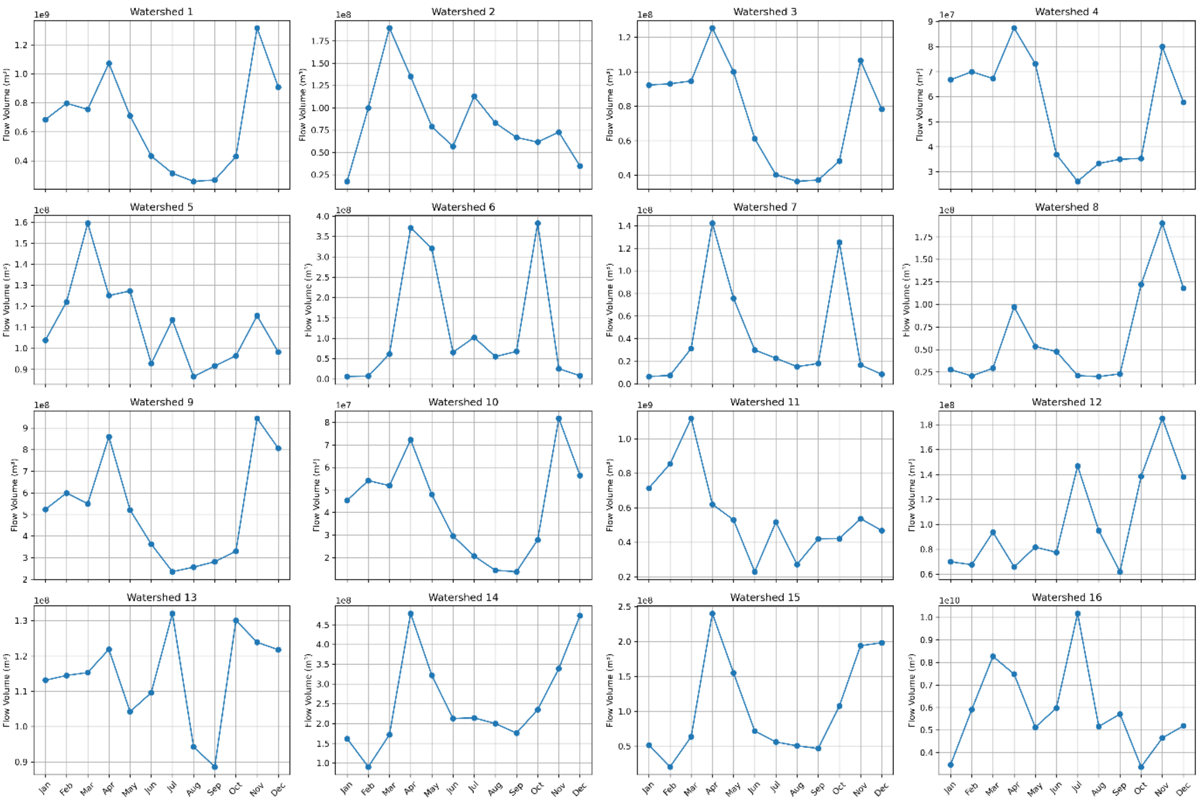
Monthly Flow Volume per Watershed in 2010



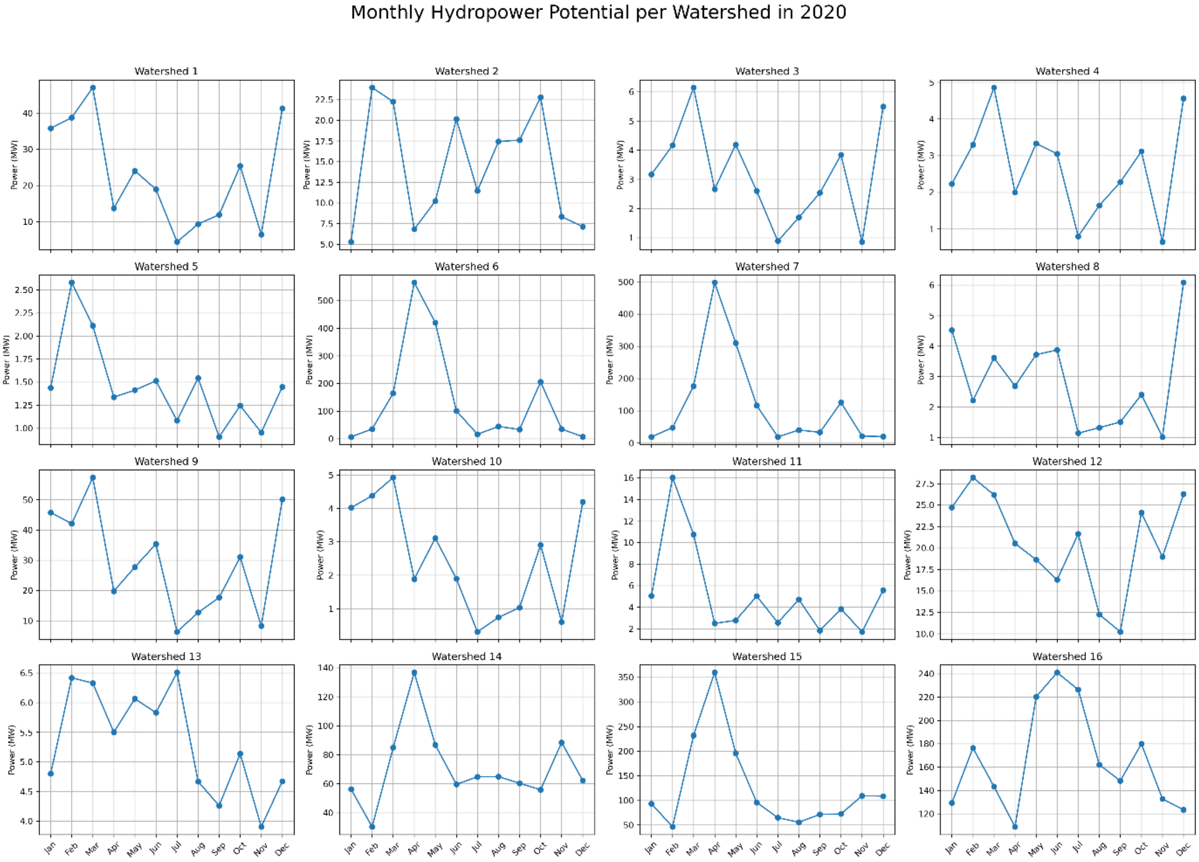
Monthly Flow Volume per Watershed in 2005

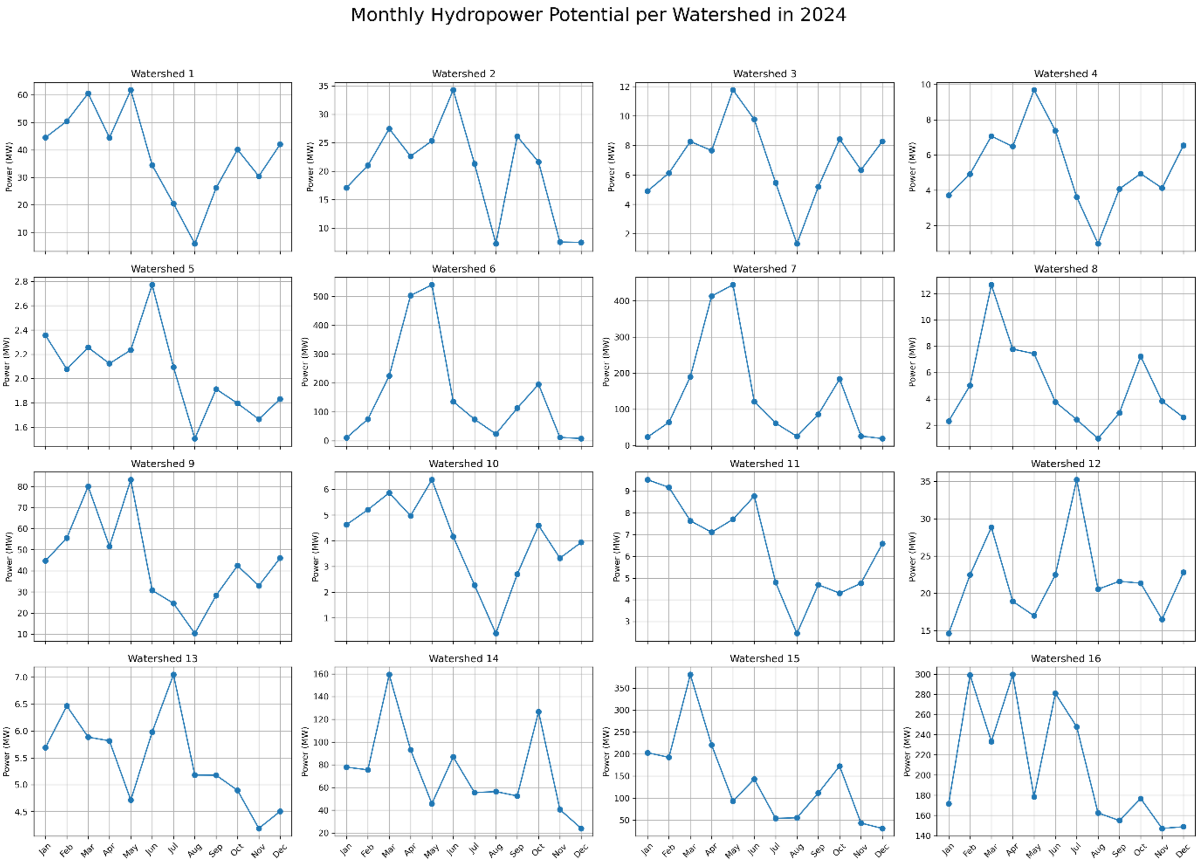


Monthly Flow Volume per Watershed in 2000

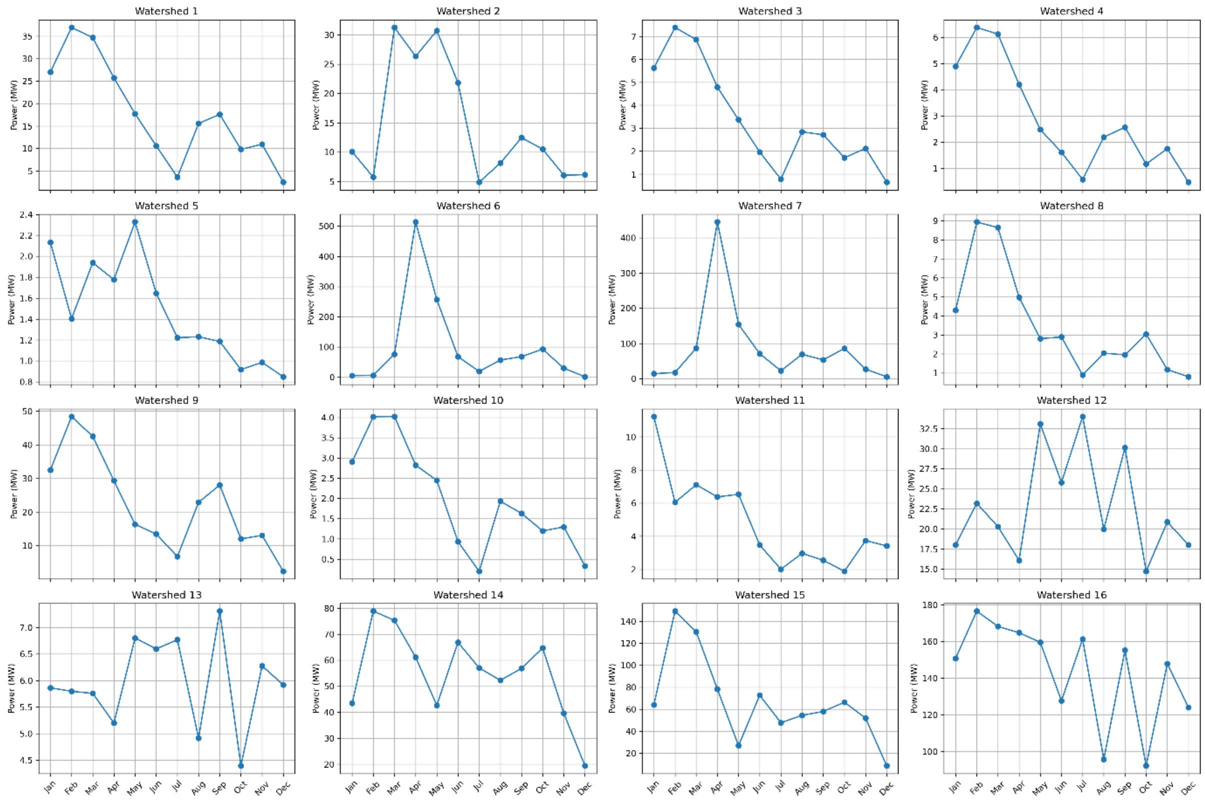


Appendix C: Hydropower monthly time series (2000 – 2024)

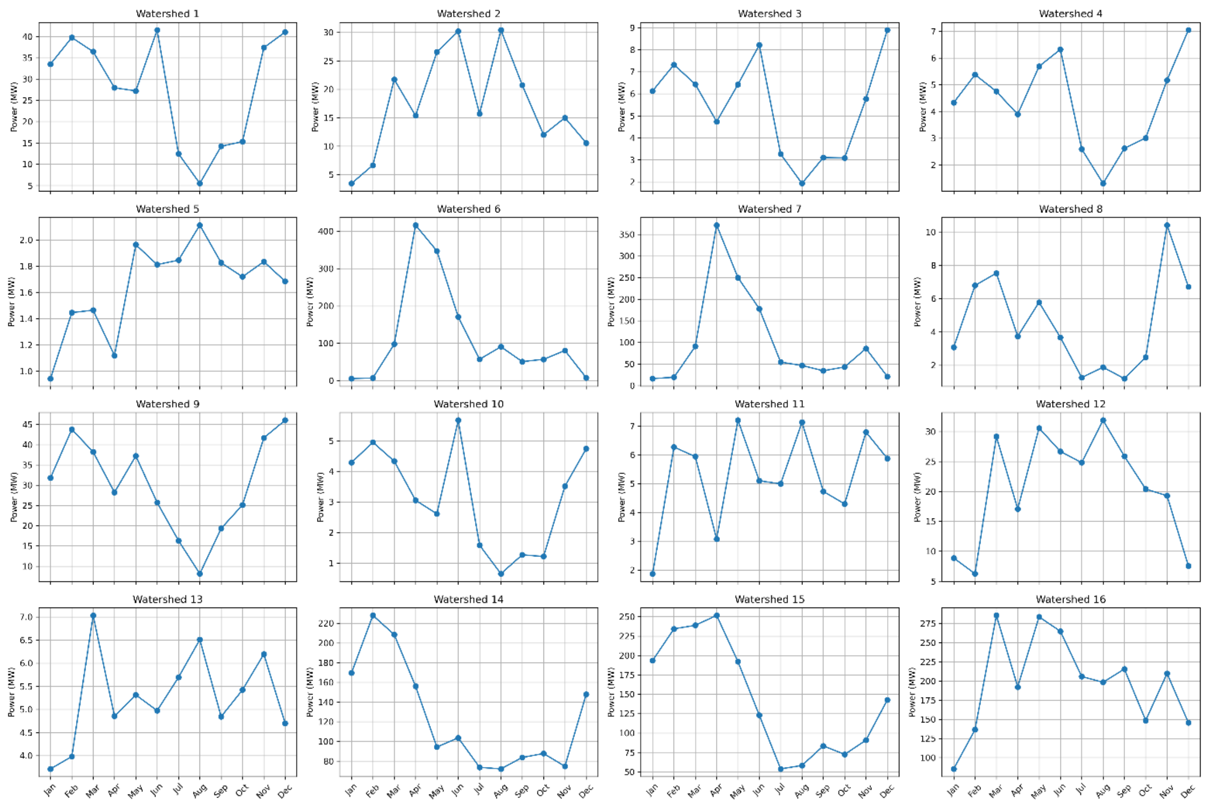




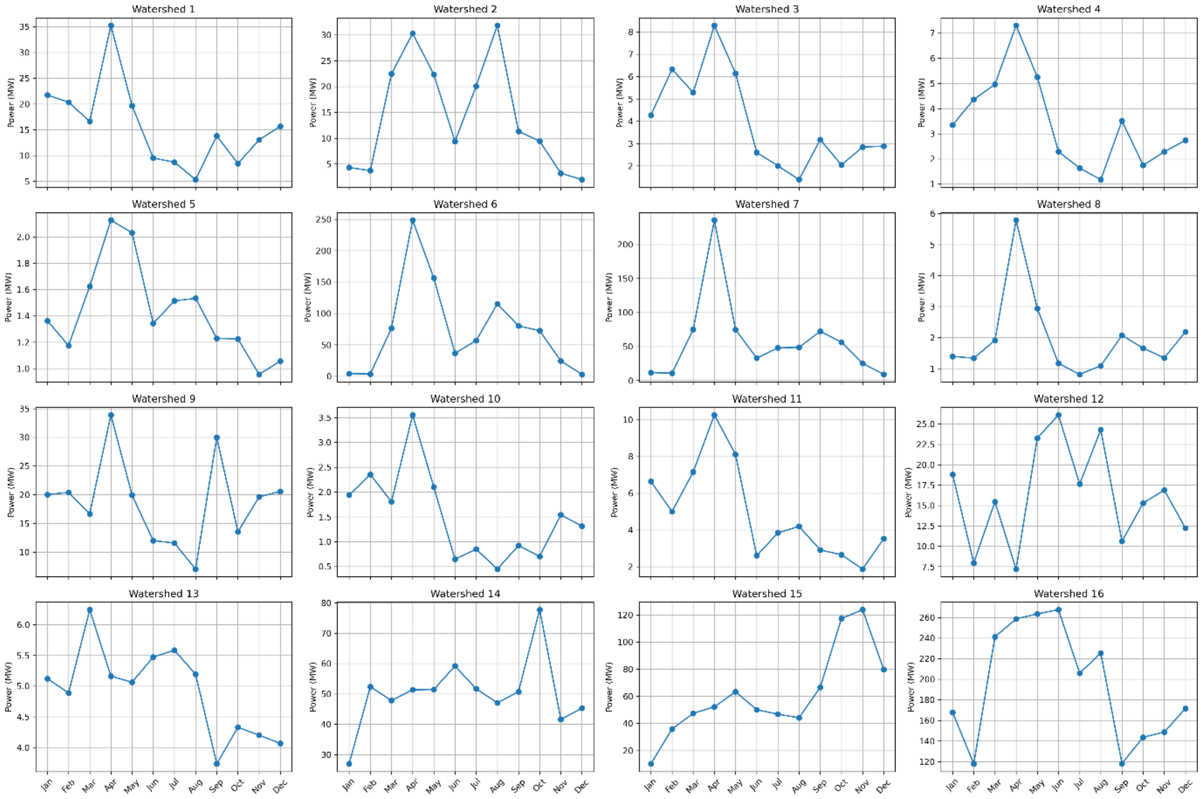
Monthly Hydropower Potential per Watershed in 2015



Monthly Hydropower Potential per Watershed in 2010



Monthly Hydropower Potential per Watershed in 2005



Monthly Hydropower Potential per Watershed in 2000