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High-resolution mapping of land use changes in Norwegian hydropower systems

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ABSTRACT

The Transition towards sustainable energy systems requires phasing out fossil fuels. Hydropower is a key source of renewable energy and can contribute to reaching a 100 % low carbon-based energy system. Uncertainty remains about land cover changes due to hydropower deployment with a widespread perception of major losses in the land from inundation and associated habitat loss in the surrounding areas due to improved access and recreational use. Norway has a dominant share of hydropower generation in Europe with knowledge gaps in the associated land cover changes. We conducted one of the first retrospective analyses of land use change associated with hydropower development in Norway during the last 80 years. Using remote sensing data, we performed object-based analysis on sets of aerial images representing land systems before and after hydropower construction. We quantified the change in the land due to development of 40 hydropower schemes representing 24 % of the total Norwegian installed capacity. Our analysis revealed that 88 % of analyzed reservoirs were developed by regulating or expanding natural lakes. Vegetation growth was observed in the surrounding regions of 22 of 40 schemes, while urbanization was limited to only 0.9 % of the total surrounding area, primarily located within 400 *m* from reservoir's borders. Our findings provide insights into interaction between land use change and hydropower development in Norway. Our work provides a basis for further assessment of relevant environmental impacts and can be used to quantify expected land changes due to an increase in Norway's hydropower with integration into the European energy market.

1. Introduction

Climate change and an increasing demand for energy require a rapid transition from a fossil-based energy system to a low-carbon energy and the development of new energy sources, which necessitate the development of innovative and sustainable energy solutions [1]. Hydropower is the dominant source of renewable energy worldwide that accounted for almost twice the combined energy production of solar and wind power as of 2020 and is expected to continue growing [2]. Hydropower stands as a crucial renewable energy source in a paradigm shift toward sustainable energy production, offering the advantages of both flexibility and sustainability [2]. As a low-carbon energy technology, hydropower offers a compelling solution for mitigating climate change and curtailing greenhouse gas emissions both directly as a clean source of energy, and indirectly by stabilizing the fluctuations inherent in other renewable energy sources [3]. These attributes position hydropower as a key element in the green transition goals outlined by the European Union toward climate neutrality [4]. Besides the production of renewable energy, storage hydropower systems also provide of water-related services such as supplying water for irrigation and drinking and mitigation measures for droughts and floods. The provision of this diversity of services places hydropower with reservoirs at the center of several of the united nations sustainable development goals (SDGs) including the provision of affordable and clean energy (SDG 7), mitigation of climate change (SDG 13), security of supply of drinking water in countries at risk of water shortage (SDG 6), reduced inequalities (SDG 10), zero hunger (SDG 2) and life on land (SDG 15) [5].

However, hydropower also poses significant environmental challenges, particularly during the construction and operational phases [6]. One significant environmental concern linked to the development of hydropower is its potential to induce land use and land cover change. Such changes are amongst the most significant threats to biodiversity and ecosystem services, as well as directly impacting fish and other

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Nomenclature

Abbreviations

EU	European Union
SDGs	Sustainable Development Goals
Norge i Bilder	The Norwegian portal for aerial images database
NVE	Norwegian Water Resources and Energy Directorate
HRWL	Highest Regulated Water Level
GLCM	Gray Level Co-Occurrence Matrix
CART	Classification and Regression Trees
LBP	Local Binary Pattern
CLBP	Completed Local Binary Pattern
RGB	Red, Green, Blue
HSI	Hue, Saturation, and Intensity
GIS	Geographic Information System
GDAL	Geospatial Data Abstraction Library
SVM	Support Vector Machine

Symbols/Notations

CLBP_S	Sign component of completed local binary pattern
CLBP_M	Magnitude component of completed local binary pattern
CLBP_C	Center gray component of completed local binary pattern
R	Radius parameter of local binary pattern
W	Moving window size of gray level co-occurrence matrix
S	Step distance of gray level co-occurrence matrix
Ø	Direction of estimation of gray level co-occurrence matrix

Units

m	Meters
km	Kilometers
km^2	Square Kilometers
ha	Hectares
MW	Megawatts
GW	Gigawatts
h	Hour

aquatic species due to the construction of dams and changes in the natural flow regime in the affected watercourses [7–9].

The physical changes to land use and land cover resulting from hydropower deployment can be divided into two primary categories. First, a zone of direct impact which encompasses the land permanently occupied by hydropower components. The zone typically includes areas inundated due to the damming of watersheds, and land occupation by hydropower infrastructures such as dams and powerhouses [8]. A second category includes a zone of transformed land with secondary or indirect cause-effects related to hydropower development. The zone may include roads that were made initially for the construction of hydropower facilities, which increase the exposure of the surrounding land to anthropogenic influence that can lead to any form of land occupation or degradation in the surrounding region [8]. Both categories of land use changes can result in significant consequences for ecosystem service. The changes can pose a threat to biodiversity [10,11], alter the natural carbon storage cycle [12,13], and contribute to soil erosion, and problems with sedimentation [14]. Furthermore, land use changes can be a driving force in transforming socio-economic conditions, potentially escalating competition over land induced by factors such as increased resettlement or agricultural land expansion [12,14].

The characteristics and extent of the land use changes can significantly vary depending on the design of the hydropower systems and the particular regions where development has been implemented. Research on land use effects has been restricted to localized case studies, each of which primarily focuses on the impacts that are relevant to the specific region in question [8,15].

Studies have investigated the physical changes induced by different hydropower systems and the relevant resulting impacts typically through use of available remote sensing data sources to map effects before and after construction to quantify change in land systems and associate these changes with different types of impact [16,17].

Major knowledge gaps remain in understanding the environmental impacts caused by hydropower in Europe where rapid advancement towards green transition is occurring [7]. In Norway, which has more than 50 % of the reservoir storage capacity and 20 % of the annual hydropower production in Europe [18], there is limited knowledge on the footprint and impact of the land occupations that resulted from this development. A majority of Norwegian hydropower systems were constructed between 1950 and 1980 [19,20], a period from which comprehensive image sources to capture the resulting environmental changes are scarce. A lack of aerial imagery presents a challenge in accurately understanding the full extent of landscape alterations due to these early installations.

Previous studies developed methods for comparing the land occupation of different renewables using different indices [21] and quantified the land area occupied by the Norwegian reservoirs [22]. However, the composition of the land that was used for this development in Norway remains unknown. Furthermore, the response of the surrounding land system remains unclear. Deployment of hydropower facilities can lead to additional pressure on surrounding lands. Energy development can lead to vegetation loss, which is indirectly caused by the increase in human presence and urbanization based on access roads initially constructed for the hydropower systems [23].

Addressing the existing knowledge gaps around the impacts of hydropower infrastructures is crucial for evaluating the potential implications of future European energy scenarios [24]. With Norwegian hydropower envisioned as a backbone for various levels of integration, serving both as a primary energy provider and as a balancing mechanism for wind power and other intermittent sources of renewable energy [25], an understanding of its environmental footprint becomes imperative. Moreover, bridging these knowledge gaps is pivotal in guiding policymakers and energy producers in the strategic planning and development of future hydropower projects. Detailed insights into land use changes induced by hydropower installations will enable decisions that optimize land use, locating future projects where they can maximize energy production while minimizing ecosystem impacts.

This study thus aims to evaluate the tradeoffs between meeting our energy needs and optimizing the land use, contributing significantly to the sustainable development of the hydropower industry. A better understanding of the land use changes, and environmental footprint associated with hydropower will be pivotal for robust planning and sustainable development of the energy sector.

To address the knowledge gaps concerning hydropower footprints and impacts within a European context, this study's primary goal is to contribute to this limited body of knowledge on the interaction between land use and hydropower development. We have conducted a retrospective analysis of the interactions between land dynamics and hydropower development in Norway. We address three key questions in this study: i) What are the land systems used for the development of hydropower in Norway? ii) How has the surrounding land reacted to this development? iii) To what extent has development induced the change surrounding the land systems?

To answer these questions, the study objectives were to use available remote sensing data and new spatial tools to investigate and quantify land use changes induced by hydropower development in Norway, and to compare land systems before and after this development.

2. Data and methods

2.1. Basis of land use change assessment

The main basis for assessment in the study was to compare the land systems containing hydropower schemes before and after development. By doing so, we are able to: i) Identify and quantify the type of land that was directly used for the hydropower components and water storage. ii) Investigate any indirect effect that has been caused by this development over the time. iii) Determine the spatial extent of indirect effects if they are present.

To identify the land use impacts associated with a hydropower scheme, we first defined the main components of a typical hydropower project. In Norway, a large hydropower system (>10 MW) usually consists of five key elements. As illustrated in Fig. 1, the elements include: i) One or more reservoirs where water is stored for power production regulated by one or multiple dams. ii) Brook intakes where water is transferred directly to the power plant or to the reservoir to allocate the water. Brook intakes include a dam without any inundation of the surrounding land. iii) Tunnels for transferring water from the reservoirs and brook intakes to the iv) powerhouse and turbines, for generation and distribution of electricity. v) Associated structures with the hydropower construction, such as roads which were built mainly for the construction process of the hydropower system. Construction deposits and debris from drilling the tunnels are also included, and in most cases, located in the surrounding region of the hydropower system.

We set a buffer area of 1 km and 0.5 km around reservoirs and brook dams respectively as a boundary of the extent that might be influenced due to the hydropower components themselves. We used a buffer extent of up to 1 km to avoid overcounting different surrounding land change drivers that are not related to hydropower construction. Moreover, it was also observed that most of the roads made due to the construction process exist within these buffer areas.

2.2. Data availability

Most Norwegian hydropower systems were constructed in the 1950s and 1960s and it was difficult to find satellite images showing the relevant land systems prior to development. Furthermore, many Norwegian hydropower systems consist of relatively small reservoirs (<10 km^2) scattered across the country. The development framework and the area extent would make it difficult to identify the relevant land classes prior to the development of these hydropower systems due to the relatively coarse resolution of the early satellite images (60 *m* per pixel).

The Norwegian mapping authority provides aerial images in a dataset portal (Norge i Bilder) that contains aerial images that go back to 1930 with a high-resolution scale between 20 and 50 cm per pixel. We obtained the aerial images which were used to identify the land systems prior to most of the Norwegian hydropower systems development from the database. We went through all available images at the portal and selected all the existing images that covered sites of hydropower systems before their construction.

Additionally, we obtained recent aerial images for the same subset of areas which were used to compare the current land composition with the status before the hydropower development. To assess the footprint of hydropower facilities, we obtained a geodatabase from the Norwegian Water Resources And Energy Directorate (NVE) [26] containing a vector polygon file representing the extent of Norwegian reservoirs on their

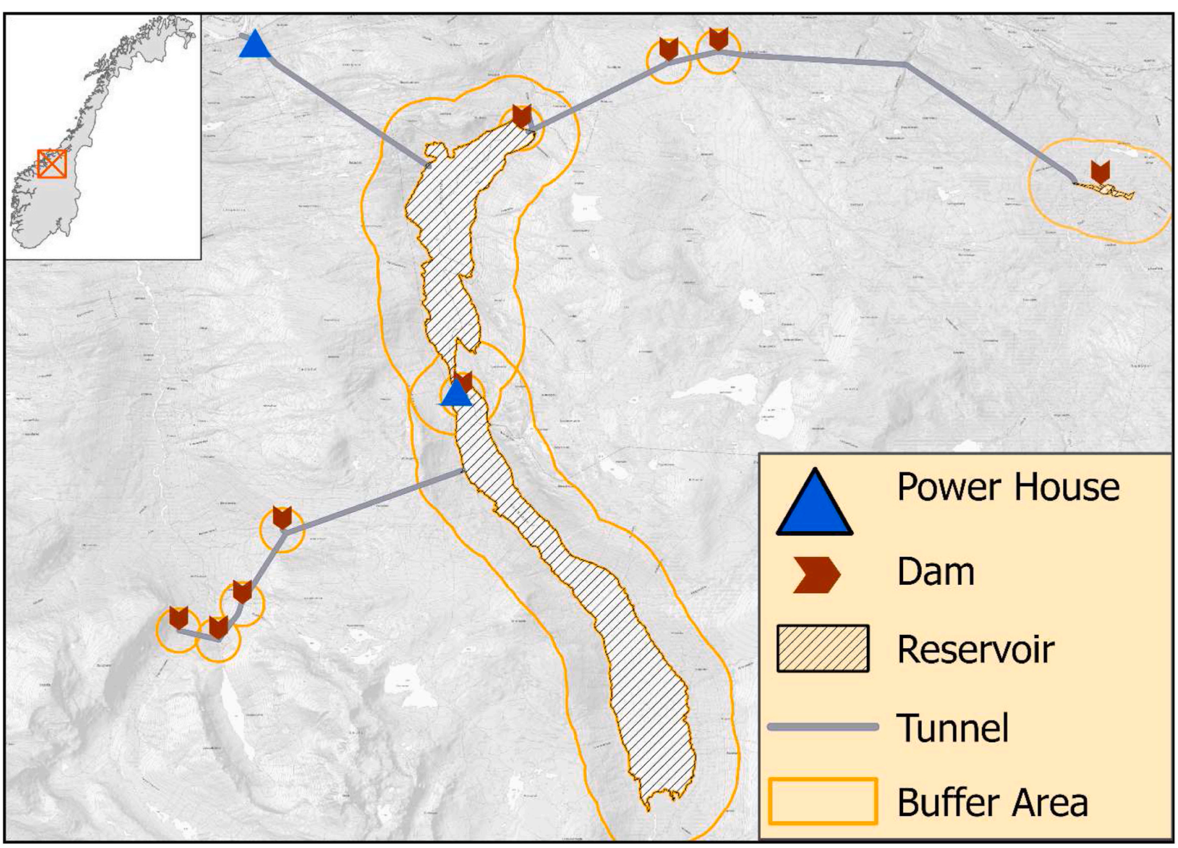

Fig. 1. Example of typical Norwegian Hydropower scheme (Trollheim) consisting of reservoirs, tunnels, and brook dams with our basis for the LU assessment. Direct occupation is associated with the reservoir area whereas indirect is associated with the surrounding extent of the hydropower components.

highest regulated water level (HRWL) which can be used as an upper boundary for the land occupied by reservoirs. The geodatabase also contains the locations of the dams, tunnels, and intakes of the hydropower plants.

2.3. Study area

We successfully compiled available aerial images before and after construction for 40 hydropower schemes. The projects accounted for 8.1 GW (GW) installed capacity which represents 24 % of the total hydropower installed capacity and 12 % of the total reservoir area. Fig. 2 visualizes the spatial distribution of the analyzed hydropower schemes with their relevant components along Norway.

The induced land use changes by hydropower depend significantly on the topography [15]. We ensured that the analyzed hydropower schemes covered all the 11 counties in Norway. Selection of representative projects was ensured by requesting and digitizing additional raw images from the Norwegian mapping authority. The available aerial images were mosaiced, georeferenced, and orthorectified using structure from motion (SfM).

2.4. Image classification

We identified five main land classes based on the CORINE first-level land classification system [27] summarized in Table 1.

The aerial images retrieved from the Norwegian portal (Norge i Bilder) provided good spatially detailed information about the land systems prior to the development of hydropower. However, early images were monochromatic and lacked spectral information, which makes it difficult to automate the classification of these images based on the spectral information alone. Additionally, a manual classification of land cover for these images would require a considerable amount of labor and time. Therefore, in the absence of spectral information, we developed an automated workflow that relied on three types of textural features as inputs for the land classification procedure.

- **Gray level co-occurrence matrix (GLCM)**

Table 1
Summary of the included land classes in the analysis.

Land class	Description
Urban areas	Includes different kinds of artificial areas that have been built by human presence such as construction waste, residential, commercial, and industrial areas in addition to artificial non-agricultural vegetated areas.
Agricultural areas	Covers different types of crops in addition to pastures and arable lands if they exist.
Vegetated areas	Includes different kinds of forestry and shrubs moors and heathland.
Water areas	Indicates land containing different kinds of water bodies such as rivers natural lakes and artificial reservoirs.
Barren and wetland areas	Includes open areas with little or no vegetation such as bare rocks, spare vegetation, glaciers, and snow areas in addition to inland marshes and peat bogs.

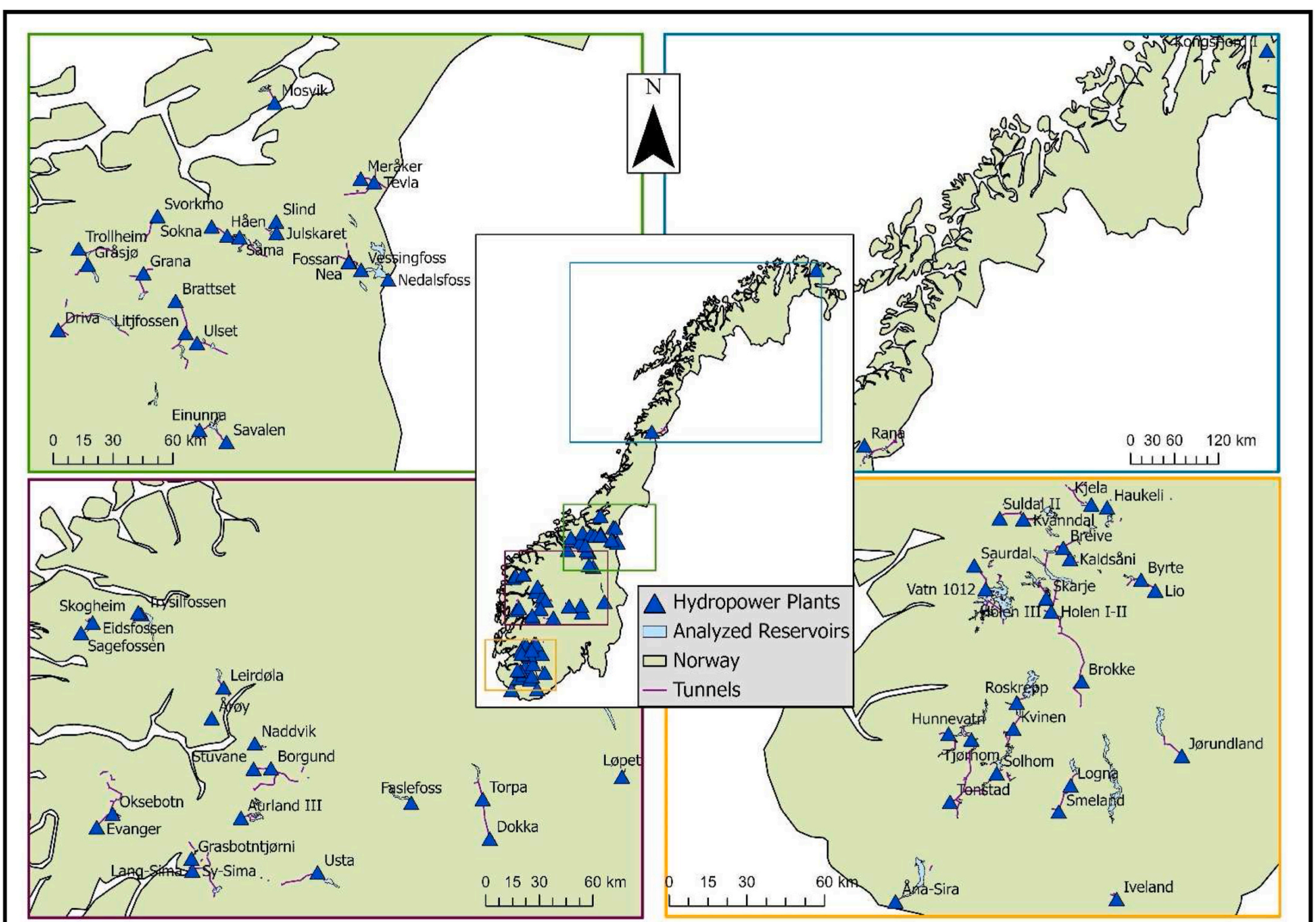

Fig. 2. Map of the analyzed hydropower schemes with their relevant reservoirs, tunnels, brook intakes, and powerhouses with their distribution in Norway. The analyzed schemes were constructed during the period 1960–1980. Scales differ among panels.

Haralick et al. (1973) developed a set of 14 statistical textural descriptors derived from the relation between the value of a gray pixel to its surrounding pixels which depend on the window size (W) used as a boundary for the calculations, the direction, or the angle of this calculation (∅) and the moving step between a pixel and its neighbor (S). Such features have proved to be efficient in image classification when there is a limitation in spectral information [28,29] or in combination with the spectral information to distinguish between different land classes [30,31].

Three parameters control the outcome of the GLCM layers: (moving window size W, the direction of estimation ∅, and the distance between the pixel and its relative neighbors S). Random samples of small image batches with ground truth sample points representing all the classes were used for estimating the optimum parameters of GLCM as well as which features to include in our classification. A Classification And Regression Trees algorithm (CART) was first used to determine which features to include in our classification procedure and under which parameters to use among different land classes. Additionally, cross-validation was used to test the overall accuracy of the resulting classification based on the used features.

A normalized GLCM was created with a 7×7 moving window size (W), 3 as a step distance (S), and a diagonal direction was used ($\varnothing = 45^{\circ}$). Moreover, features from the first order of statistics representing mean and variance in addition to Entropy, Correlation, Inertia (Contrast), and Cluster Shade from a higher order of statistics were included as input features for the classification algorithm. Orfeo Toolbox was used to create the first and higher order of statistical features of GLCM [32].

- **Local binary pattern (LBP)**

Local Binary pattern is a rotational convolution filter that defines the relationship between a center pixel on a gray level and its surrounding number of pixels P within a radius R. It creates a binary pattern representing the difference between the center pixel and its neighbors [33].

Multiple improvements have been made to the original LBP filter that aim at increasing its efficiency for image recognition [34–37]. Here, we used Complete Local Binary Pattern (CLBP) [35] which generates two additional filters in addition to the original filter (CLBP_S) marking the absolute difference between the center pixel to its neighbors (CLBP_M) and a binary filter that marks the difference between each pixel and the to the average gray value of the entire image patch (CLBP_C). Additionally, we applied a median filter (LBP Med) to the original LBP (CLBP_S).

- **Original monochromatic features**

The textural features were combined with the original panchromatic band after normalizing the image to remove global intensity and applying an additional median filter with a window size of 15×15 to remove the local contrast between neighboring pixels. Fig. 3 summarizes the total three textural features and 12 nested parameters were used for classifying the historical aerial images.

Recent aerial images for the hydropower schemes were more modern and included three color bands. The textural features from the monochrome images were included in preprocessing of recent colored aerial images that have recorded the current status of the land composition. However, we included the spectral information representing the RGB bands in addition to hue, saturation, and intensity (HSI) as additional information to distinguish between the land classes.

Preprocessing high-resolution images usually consumes the most time and resources of the computation machine. Moreover, all the above textural operations are particularly complex operations that would take considerable time to process. To overcome challenges with computation time, all the tools that extract the key features from aerial imagery were compiled together in Python where image batches at a scale of 1:5000 and preprocessed in parallel on multiple 64 cpu cores.

All of the associated features were then mosaiced together and aggregated with other features using GDAL as a raster data processing container [38] which has an advantage over other GIS environments for its efficient processing time.

An object-based classification was performed on both the historical panchromatic images as well as the recent colored ones using eCognition Developer 10.2 [39]. Multi-resolution segmentation was performed on the mosaiced image using a scale of 100/60 for images with resolutions of 20 and 50 cm respectively with a shape of 0.2 and a scale of 0.8.

After segmentation, random training samples representing every land class were mapped where a supervised classification was performed using support vector machine (SVM) with a radial kernel [40]. Hyper-parameter estimation for the classifier was performed using a random

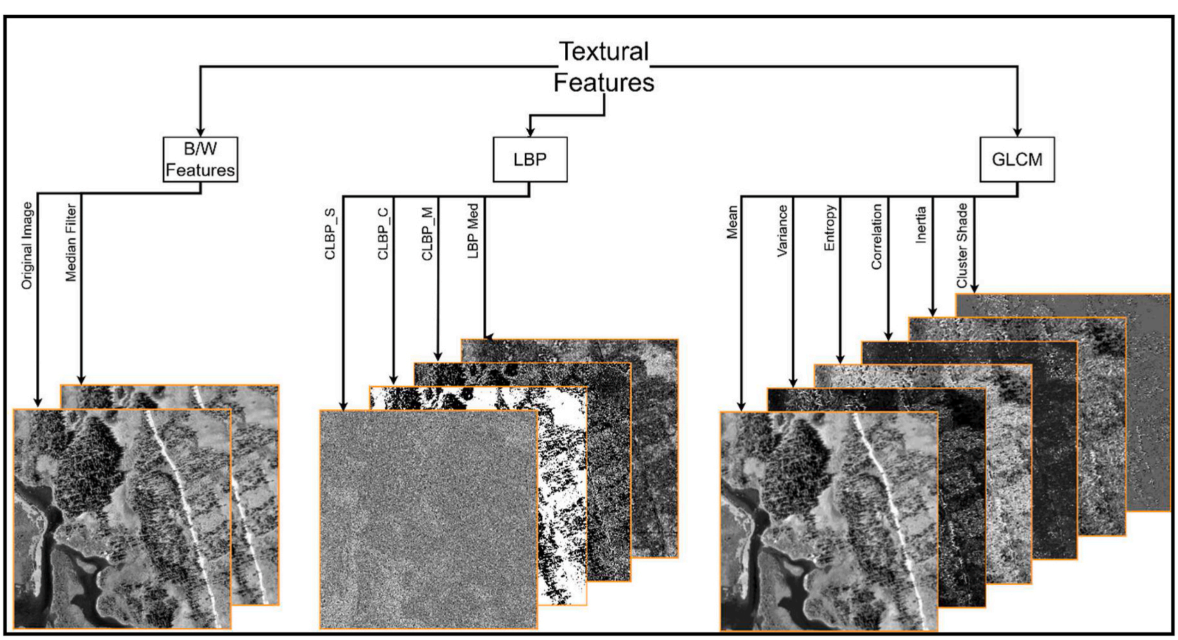

Fig. 3. Textural features that were included as input for the classification of the aerial images. B/W: Black and White, LBP: Local Binary Pattern, GLCM: Gray Level Co-occurrence Matrix.

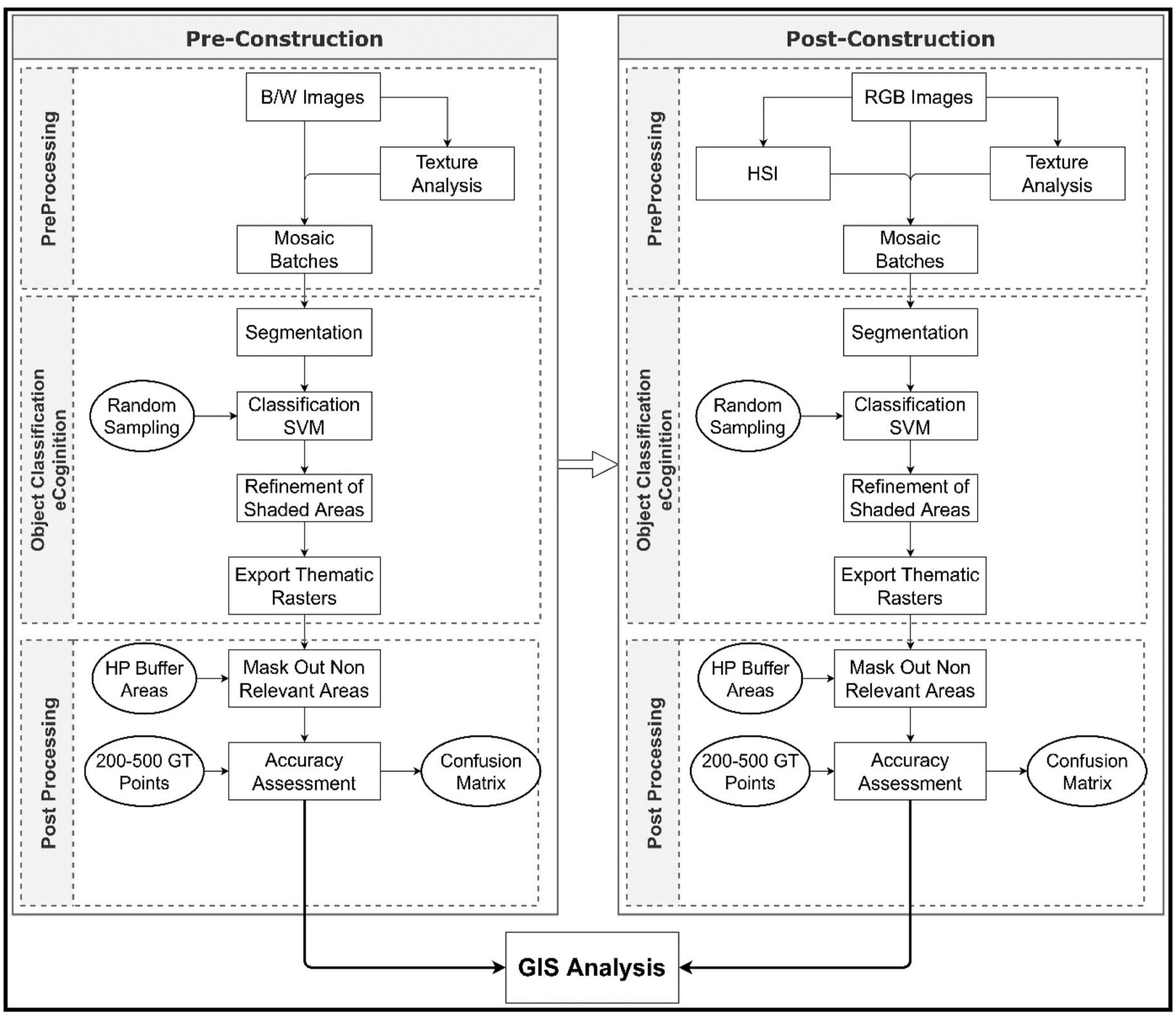

Fig. 4. Summary of the workflow representing the procedure of processing the retrieved aerial images. B/W: Historical aerial images, RGB: Recent colored images, HSI: Hue, saturation, and intensity, SVM: Support vector machine.

grid search based on the random samples.

One challenge with aerial images is that the quality of the image source can be easily influenced by the extent of the shaded area. In the case where historical images were monochromatic shadows can affect the quality of the classified areas significantly. To overcome this problem, a manual refinement to the classified images was done inside the eCognition environment where shaded areas existed in the image patches to increase the overall accuracy of the resulting classified image [41].

The classified images were then exported as thematic rasters to ArcGIS Pro 2.9 [41] where the non-relevant areas outside the hydropower buffer zones extent were masked out. Accuracy assessment was performed using 200–500 equalized stratified random ground truth points depending on the existing land classes and the extent of the surface area of each thematic raster. Two confusion matrices were generated for each hydropower scheme representing the classified images to assess the error rates in misclassified land classes. Fig. 4 shows the standarized workflow for the classification and analysis for both image sources.

2.5. Quantification of land use changes

The masked rasters representing each scheme before and after the construction were combined and resampled to 0.2 *m* per cell to ensure all images had the same pixel resolution. Additionally, the shape files representing the Norwegian hydropower components were overlayed and the categories of assessment for direct and indirect effects were quantified as follows:

First, the directly impacted land by the occupation of hydropower schemes was limited to the occupied land by the reservoirs because that was the biggest component. Quantification of the occupied land was estimated by overlaying the shapefile representing the relevant reservoir for each scheme with the classified images before the development.

Second, the indirect effects caused by the deployment of a hydropower system can be identified by the proxy of urban development that can be caused due to the increased possibility of exposure to isolated land using the roads that were made originally for installing hydropower structures. Such exposure can be a potential for vegetation loss which can be reflected in the loss of biodiversity.

To identify the indirect impacts, the classified images were overlayed for each scheme and a change raster was generated to identify the change among the land classes between the two image sources. We categorized the indirect effect mainly by the change in urban and vegetation classes as the two classes of landcover were a clear direct indicator reflecting this indirect impact. The hydropower components represented by dams and intakes were mapped in the urban category. The footprint of the infrastructure was usually small and would be negligible if estimated separately. Additionally, the calculated direct occupied areas were masked out from this calculation to distinguish between the different types of impact.

Last, it was unclear to what extent hydropower development might affect the surrounding region. To determine the extent of impacts in adjacent areas, the quantified indirect effects were mapped in every 100 *m* and 50 *m* buffer zones around reservoirs and brook dams respectively where in each zone the changes in the land categories were quantified.

3. Results

We classified aerial images representing 40 hydropower schemes that included 70 hydropower plants, 105 reservoirs with a total area of

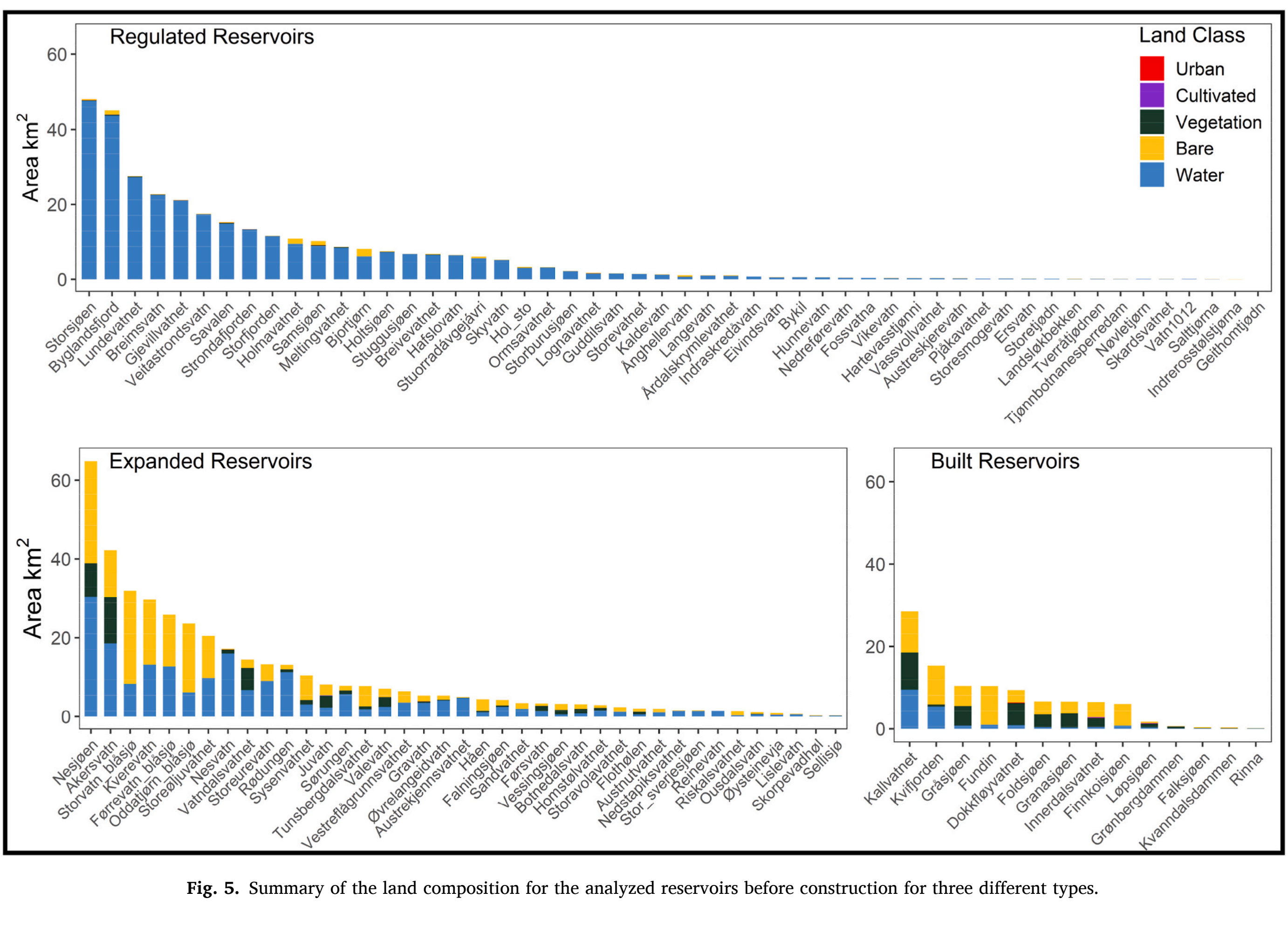

Fig. 5. Summary of the land composition for the analyzed reservoirs before construction for three different types.

Table 2
Summary of the total occupied area per land class and reservoir type in km.^{2}.

Reservoir Type	Land Class	Sum Per Land Class km^2	Total Area Used km^2
Regulated	Bare	9.32	**322.96**
	Cultivated	0.07	
	Urban	0.15	
	Vegetation	1.86	
	Water	311.56	
Expanded	Bare	165.94	**400.45**
	Cultivated	0.10	
	Urban	0.09	
	Vegetation	42.56	
	Water	191.76	
Built	Bare	52.84	**103.33**
	Cultivated	0.28	
	Urban	0.24	
	Vegetation	30.06	
	Water	19.91	

837 km^2, and 48 brook dam points. The historical image dates ranged from 1950 to 1975 which provided the needed baseline information about land use and cover before hydropower development. We evaluated the accuracy of land cover classifications and then determined the for the associated land use changes by the analyzed hydropower schemes.

3.1. Accuracy assessment

An accuracy assessment was performed on all the classified areas and confusion matrices were generated using the ground truth sample points for each regime. The overall accuracy of the classified images was good and ranged from 85.4 % to 98.7 % with an average value of 91.8 %.

3.2. Direct land occupation

By combining the classified historical images with the shapefile representing the reservoirs at their highest regulated water level we were able to identify the land systems used for this occupation. Based on the land composition from before/after comparisons, we were able to identify three main patterns for locations developed for hydropower schemes. These patterns as shown in Fig. 5, include.

- **Regulated reservoirs,** included natural lakes that were developed for hydropower production without altering their inundated area or with a negligible level of change that didn't exceed 1 % of the total reservoir surface area. A majority of the sites in this study were regulated reservoirs (52 out of 105 reservoirs, 49,5 %).
- **Expanded reservoirs,** consisted of some existing small lakes utilized for hydropower production which resulted in an increase in the inundated areas due to the dam construction. About a third of the sites in this study were expanded reservoirs (39 out of 105 reservoirs, 37,1 %).
- **Built reservoirs** were newly constructed on water courses or river streams combined with different land classes. Relatively few sites were newly built reservoirs (14 out of 105 reservoirs, 13,3 %).

The land composition varied among the three categories of reservoirs where water bodies were the main land class in the regulated and expanded ones with more than 90 % in the regulated ones and a lower value in the expanded ones. Results also show that vegetated land was occupied with a higher percentage in the category of built reservoirs.

Regulated reservoirs were more common in this study, but extended reservoirs dominated the altered land with 48 % of the occupied areas. Additionally, built reservoirs represented 12 % of the occupied land as summarized in Table 2.

3.3. Land change surrounding hydropower schemes

We quantified changes in vegetation and urban areas within buffer zone around each hydropower schemes. We observed an increase in urban areas in all schemes, ranging from 0 to 2 km^2, with mean and median values of 0.25 and 0.1 km^2, respectively.

In terms of vegetation changes, a slight majority of schemes (22 out of 40) had vegetative growth in the buffer region surrounding the reservoir. Conversely, six schemes reported a loss in vegetation, the greatest decrease being less than 1 km^2. The remaining 12 schemes demonstrated no significant change in vegetation. These patterns of urban and vegetation changes surrounding the hydropower schemes are

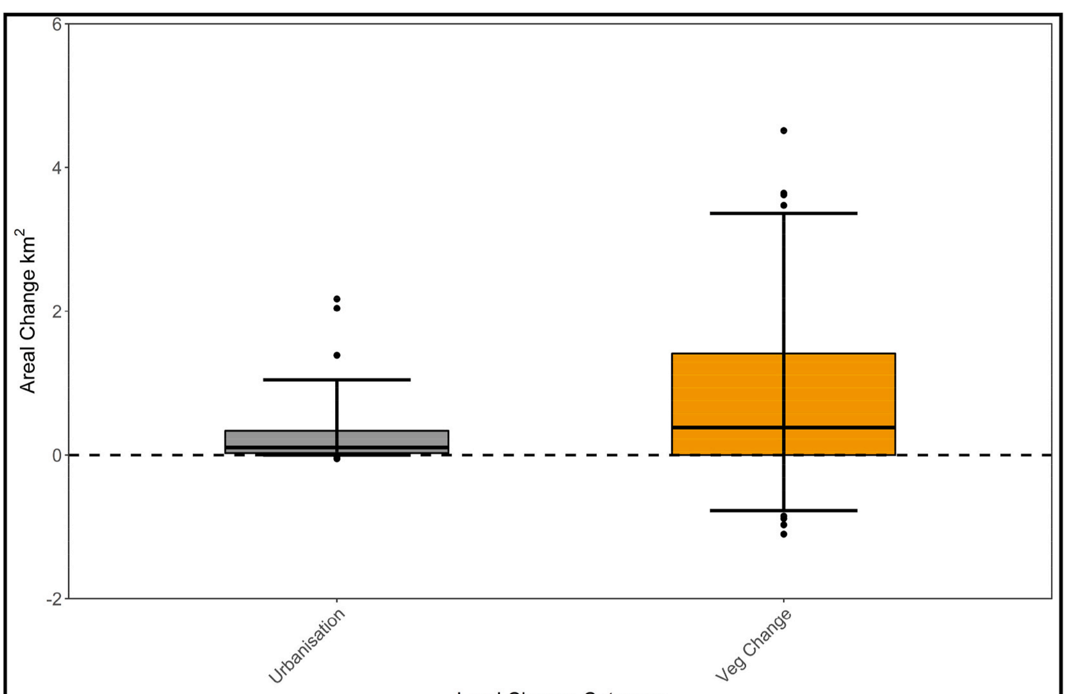

Fig. 6. Aggregated boxplot for the change in urbanization and vegetation change surrounding all the hydropower schemes.

detailed in Fig. 6.

3.4. Influence distance

The quantified change in vegetation and urban areas surrounding the reservoirs and dams was mapped and quantified in divided buffer zones. The urban change was mapped in equally distributed 100 *m* buffer segments surrounding the reservoirs. Results representing each layer were aggregated from all the reservoirs bounding regions. The first buffer segment always contained the biggest share of urban change throughout the whole region with a median value of 37 ha. The distribution of urban change in each buffer zone was less than 5 ha in all other buffer zones as shown in Fig. 7. Additionally, urban change was negligible and statistically insignificant ($p = 0.005$) from the fourth buffer segment onward compared to the first 400 *m* from the reservoir's borders.

Changes in urban and vegetation in the brook intake regions were mapped with similar method to the reservoir surrounding region but with 50-m segments. We found a relatively equal distribution of urban change throughout the buffer zones with an average of 0.07 ha. Additionally, a reduction in vegetation growth was observed in the first three zones up to 150 m from the dam point whereas overall vegetation growth tends to have a constant growth pattern. Fig. 8 summaries the change in urbanization and vegetation in each buffer zone surrounding the brook intake dams.

4. Discussion

In this study, we developed a new workflow based on Object-Based Image Analysis (OBIA) to quantify the changes in land use induced by the development of Norwegian hydropower. Our analysis focused on sets of aerial images, enabling us to compare the land composition before and after the development. With the novel methods, we obtained the first-ever estimates of land cover requisitioned for the establishment of 105 reservoirs for hydropower facilities. The reservoirs covered a total area of approximately 830 km^2, which represents approximately 12 % of the total surface area dedicated to reservoirs in the current Norwegian hydropower production system.

From the object-based image analysis, we discovered that a significant portion of the reservoirs (86.6 %) were developed by either regulating existing natural lakes or expanding them substantially. Conversely, a smaller proportion of sites (13.3 %) involved the creation of new reservoirs on varied land compositions or minor watercourses.

Our new findings for hydropower schemes in Norway are quite different from development trends for global hydropower, where substantial land inundation due to dam construction is more common [23, 42]. Here, urban or agricultural land encroachment was minimal, contrasting with regions where development often lead to further land use change caused by resettlement [14]. Urbanization within a 1 km buffer of our schemes was minor, averaging only 0.9 % of the surrounding surface area. This differs from other regions where hydropower frequently catalyzes urban expansion or instigates resettlement issues [16].

The practice of developing hydropower in Norway, primarily through exploiting existing lakes for reservoirs, offers valuable lessons for policy implications. Norway is endowed with a multitude of natural lakes [43] and many of these have formed the basis for hydropower reservoirs. The national development approach minimizes common adverse effects associated with hydropower projects, such as resettlement, flooding of cultivated lands, greenhouse gas emissions, and disruptions to wildlife migration routes [7]. Therefore, policymakers in regions contemplating hydropower expansion should consider leveraging existing water bodies when possible.

Incorporation of object classification, along with the utilization of high-resolution textural features, proved to be a highly efficient approach for extracting essential land use information from historic aerial images. The methodology effectively bypassed the limitations imposed by spectral information, resulting in accurate insights into the land use composition. Notably, the high overall accuracy value achieved through this approach further establishes the reliability of the classified

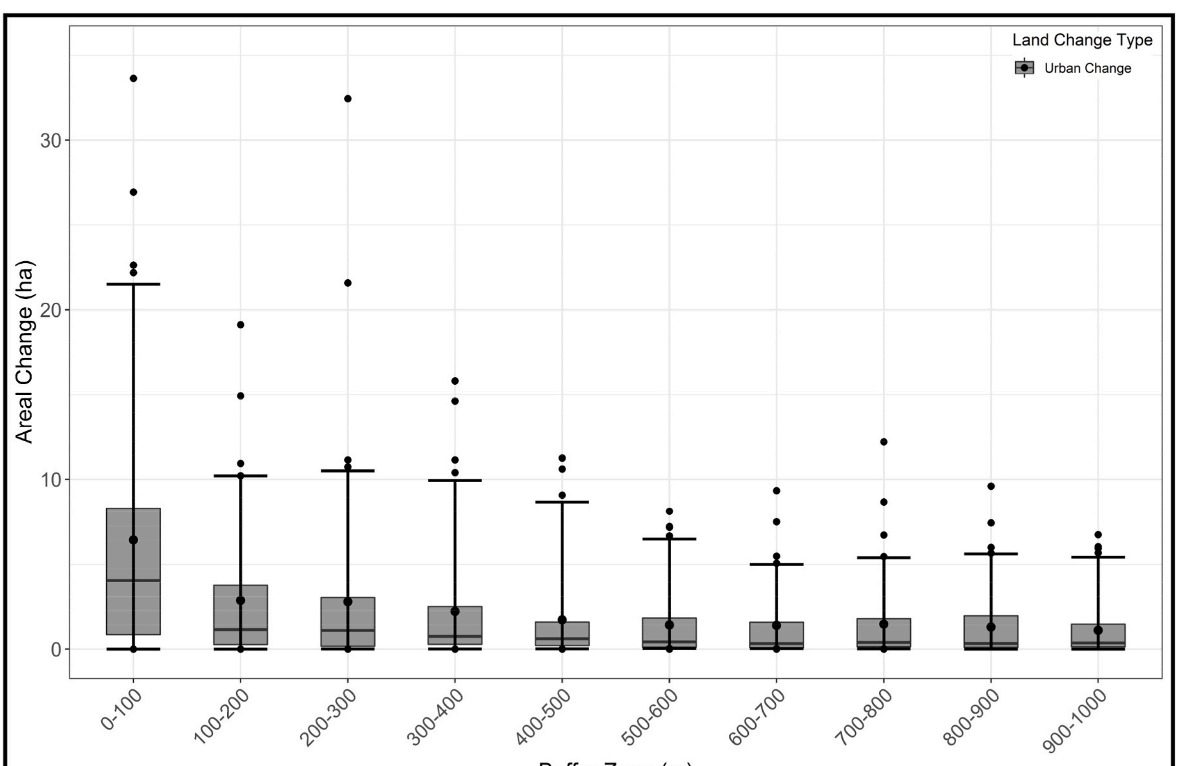

Fig. 7. Boxplot of the aggregated results regarding urban change within 1000 m of the surrounding reservoirs region divided every 100 m.

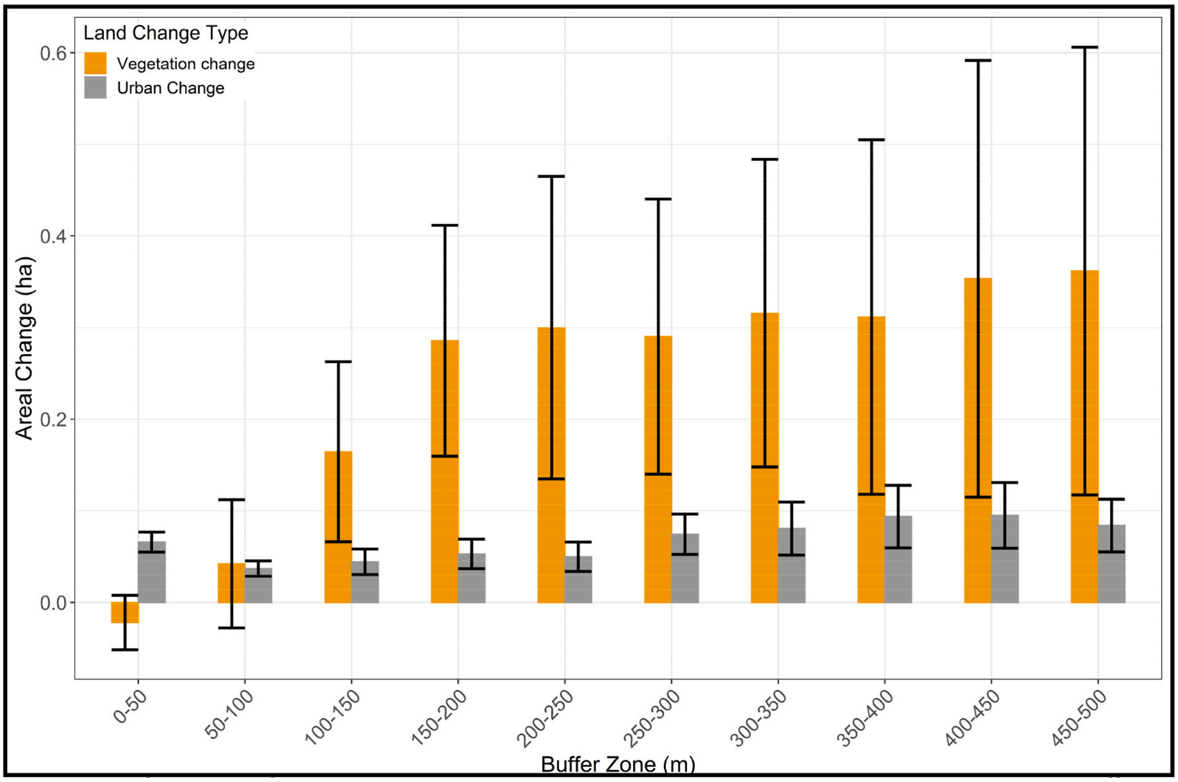

Fig. 8. Summary of the average change in urbanization and vegetation within each 50-m buffer zone surrounding the brook intakes, represented with standard error bars.

images as a valuable resource for future analyzes [44].

In addition to the high accuracy rate, each classified set of images was visually inspected to ensure the quality of the classification and to avoid problems with obvious misclassified objects. Classification errors were mostly due to the shaded areas which had to be manually interpreted and refined [45].

The quality of images from the data portal (Norge I bilder) affected the overall accuracy of the resulting classified maps as it was observed that some of the image sources suffered from low quality and high distortion errors during the digitization process. Nevertheless, the accuracy results were similar between the monochromatic and the colored images due to the absence of some land classes in the historical images which were then observed in the more recent ones, particularly urban and cultivated areas.

Applying buffer layers to the classified images was effective for spatially mapping land dynamics [46]. In the case of reservoirs, urbanization was primarily concentrated within 400 *m* from the reservoir borders, with associated elements such as roads. The first zone <100 *m*, encompassing hydropower structures like dams, roads, and gatehouses, exhibited the highest rate of urbanization. For brook dams, a reduced buffer distribution of 50 *m* was sufficient because the effects urbanization were minimal. However, vegetation changes indicated forest clearance up to 150 *m* around dam constructions. The buffer analysis findings provide valuable insights into the limited influence around of hydropower components <400 *m*, which differed from previous studies of hydropower projects where the impact extent could reach up to 10 km depending on scheme size and location [46].

4.1. Limitations and future work

Our comparisons of land cover before and after hydropower development were restricted to sites where aerial imagery were available. One challenge was that most of the images prior to the development of the schemes were available only for specific dates which created uncertainty about the amount of existing inundated areas before regulation. We overcame uncertainty by manually interpreting the classified reservoirs during the month of the image capture to match images with the typical hydrological cycle where lakes and reservoirs are at their HRWL in the spring season during the melt of the winter snow pack. The pattern can be observed in Fig. 5 where some of the regulated reservoirs had some existing bare land which might have been due to the timing of image capture by month.

Additionally, we were not usually able to obtain additional images for the hydropower schemes either immediately after the construction or in the mid-period between the classification time steps. The coarse temporal resolution of the analyzed schemes restricted our ability to observe a detailed vegetation response to hydropower development over time. We found that the surrounding vegetation was able to recover from potential impacts, but the temporal recovery of this vegetation remains unclear as there is evident observation of natural growth of vegetation in the recent years [47]. Moreover, we were unable to map the extent of vegetation clearance resulting from the construction process, which would have provided valuable insights into the ecological state when recovery began.

Furthermore, the coarse temporal resolution limits the quantification of the dried-out areas, and the fluctuating water levels in the littoral zones of the reservoirs. Such impacts require a monthly temporal resolution of the aerial image sources which is not available. However, the permanent occupied land is still quantified as the reservoirs were mapped on their HRWL.

This research focus was specifically centered on analyzing the land use changes induced by hydropower development during the initial construction phase. We were unable to examine the land use impacts during the operational phase of hydropower which would require more systematic collection of aerial imagery. However, it is crucial to highlight that the impacts of hydropower operation have been extensively studied and documented in various research studies [48]. Proper consideration and addressing of these impacts are essential prerequisites before embarking on new hydropower development projects.

Last, the large sample size, good image resolution used, and high accuracy rate from this study provide a robust quantification of the direct occupation of the schemes as well as their influence radius that could be further upscaled to evaluate effects of hydropower at national level in Norway. The resulted classified images can be further used for quantifying all the associated impacts resulted from land use change. Additional impacts could include biodiversity losses or alteration of the carbon dynamics and storage directly due to the reservoir regulation or indirectly due to the land change surrounding the reservoir region.

5. Conclusions

In this work, we developed a new workflow to quantify the associated the land cover changes caused by the development of 40 Norwegian hydropower schemes using OBIA on sets of high-resolution aerial images before the construction to the current state. We found that most of the analyzed schemes were developed by either expanding or regulating natural lakes (88 %) with a limited number of built reservoirs (12 %) which has a relatively smaller land occupation in comparison to different regions in the world. The amount of urbanization was limited with an average of 0.9 % of the total surrounding areas of the schemes and with an extent limited to 400 *m* around reservoirs and 150 *m* around brook dams. Furthermore, development did not limit the vegetation growth over the time which shows the ability of the ecosystem to recover from any potential impact during the construction process. Results signify the fact that the land cover change by hydropower slightly varies depending on various technological and spatial factors. The findings from this work provides a detailed insight into the physical areal effect caused by development. Additionally, it helps to understand the potential impact on future development. Last, the present work could be a foundation for more understanding and linking this physical land use change with the reflected impacts such as the potential impacts on biodiversity, and carbon storage.

Author responsibilities

Kenawi, MS is the main author of the work, Sandercock, BK, Bakken, TH, and Alfredsen, K supervised the work. Kenawi, MS designed the study, Kenawi, MS and, Stürzer, LS collected the data, and performed the image classification as well as the GIS analysis. All authors contributed text and read and edited the final manuscript.

Ethical Statement for Solid State Ionics

Hereby, I/insert author name/consciously assure that for the manuscript/insert title/the following is fulfilled.

1) This material is the authors' own original work, which has not been previously published elsewhere.
2) The paper is not currently being considered for publication elsewhere.
3) The paper reflects the authors' own research and analysis in a truthful and complete manner.
4) The paper properly credits the meaningful contributions of co-authors and co-researchers.
5) The results are appropriately placed in the context of prior and existing research.
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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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