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（アンデス熱帯氷河の下流河川における水質と植生に関する環境評価）
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論 文 内 容 要 旨

Climatic change is affecting all ecosystems worldwide, especially tropical glaciers. Tropical glaciers are suffering rapid retreats, and some of them have already disappeared. South America has more than 99% of the tropical glaciers of the world. In the Central Andes, 80% of the freshwater sources originate from the mountainous regions, affecting ecosystems and populations downstream. Many cities located above 2500 m depend almost entirely on high-altitude water stocks. The water is stored initially as ice on the mountains and gradually released by the melting process, acting as a unique water source during the dry season when rainfall is low or even absent. For that reason, research on aquatic environment associated to glaciers is highly required. Therefore, we focused on the Condoriri Glacier and its basin, which provides about 44% of drinking water to the two major cities in Bolivia (La Paz and El Alto). Furthermore, the watershed displays rich aquatic ecosystems, composed of rivers, lakes and wetlands. The weathering of the rocks and the abundant presence of aquatic vegetation influence the water quality in the river. Therefore, the aim of this research is to monitor and to evaluate the water quality and the growth of the submerged aquatic plants in the Condoriri River basin. Field observations were conducted during dry and wet seasons with the observed parameters were analyzed accordingly. Furthermore, macrophyte and water quality models were used to assess in detail about the macrophyte growth and nutrient concentrations in this river basin.

Water quality measurements were carried out in order to investigate the effects of nutrients and major ions composition on water quality formation during two different seasons and to determine the influence of glacier melting and the weathering of rocks. Analyses were further carried out on major ions, organic carbon and nutrients, and those results were used to estimate influential factors on their seasonal and spatial variations (Chapter 2). Concentrations of nutrients like silicate and nitrogen and major ions had fluctuating variations in the longitudinal direction of the river in both seasons, which was considered to be caused by the weathering of rocks and the distribution of precipitation. At the effluent from the glacier, high values of pH (8.3), electric conductivity (158μS/cm) and ionic concentrations like Ca^{2+} (1189μmol/l) and SO_4^{2+} (928μmol/l) were observed especially during the dry season. On the other hand, TOC, DOC and NO_3^- were higher in the wet season because of higher primary production and even more total precipitation (624 mm) as compared to the dry season. Water flow from glacier melting contributed to the weathering of rocks and considering the mutual relationships in ionic concentrations (Na^+/Cl^-=4, Ca^{2+}/Na^+=5 and Ca^{2+}/SO_4^{2-}=1), sources of major ions were silicates, carbonates and gypsum. Consequently, rock weathering mainly influenced the water quality of the river as the principal source of ions.

The variations of macrophyte biomass, primary production, physicochemical parameters, and nutrients levels in water and aquatic plants during dry and wet seasons were analyzed in Chapter 3. The relationships between the biomass of the submersed aquatic vegetation, the physicochemical parameters, the nutrient levels, and the primary production were realized in order to identify those factors that influence biomass and consequently, primary production. Primary production and macrophyte biomass exhibited a good agreement (R^2=0.68). The presence of the aquatic plants have influenced the metabolism of the target river during both dry and wet seasons, with a high net productivity (20.1 $gC \cdot m^{-2} \cdot d^{-1}$) in the wet season and a high ecosystem respiration (29.7 $gC \cdot m^{-2} \cdot d^{-1}$) during the dry season. Macrophyte biomass was related to the EC with a negative gradient (R^2=0.33, $P<0.03$). Alkaline pH (> 7.5) and the chemical composition of the water reflected by the high EC (132.5 $\mu S \cdot cm^{-1}$) led to decrease in the growth of the aquatic plants. Nutrient loading led to biomass increment. High transports of TOC (57.0 $kg \cdot day^{-1}$), TN (9.7 $kg \cdot day^{-1}$) and TP (7.9 $kg \cdot day^{-1}$) were measured during the wet season, likely to have been caused by the extreme variation in the total precipitation in the two seasons (624 mm during rainy season and only 19 mm during dry season).

In Chapter 4, the parameters were further evaluated and assessed using models. A water quality model and a macrophyte model were developed for the estimation of the nutrient concentrations in water and the consequent growth of the submerged aquatic vegetation in the Condoriri River. The effect of the macrophyte growth was included in the models. Influential factors such as nutrients in water and sediments, the variation of the discharge, solar radiation, and the water temperature were considered. Good agreements were observed between field measurements and model predictions of macrophyte biomass and nutrient concentrations at most of the monitoring points. The proposed models can predict seasonal changes of macrophyte biomass and water quality, despite their high spatial and temporal variations. Our findings enhanced the understanding of the impacts of physical and chemical factors on the macrophyte growth and the nutrient concentrations in water. Therefore, the models are useful for assessing the future condition of this river basin.

Future predictions of macrophyte biomass and water quality and the influence of the climatic change were analyzed in Chapter 5. The growth of the aquatic plants will be affected by climatic change, especially during wet season, with a reduction of 50% by the year 2039. Changes of the macrophyte biomass influence the nutrient concentrations in water (organic and inorganic phosphorus and nitrate). The results of the water quality model exhibited variations especially for inorganic and organic nitrogen. Predictions on water quality are crucial for the management of the future water resources.

論文審査結果の要旨

熱帯氷河は，気候のパラメータといわれるように気候変動に対して敏感で脆弱であるとされ，現在大きく注目されている。本研究で対象としているボリビア国内のアンデス高地の熱帯氷河は，下流都市の主要な水道水源となっているが，温暖化の影響により，近年では衰退が顕著となっており，将来的な水源地環境としての持続性が懸念されている。これらのことから，本研究は，自然科学的な観点および工学的，社会的な必要性の観点から，重要性の高い研究であると言える。

第1章では，既往研究の知見整理と研究の基本方針を述べたうえで，本論文の構成について示した。

第2章では，対象河川であるコンドリリ川における水質観測の結果に基づいて，栄養塩挙動および主要イオン組成の形成過程について検討を行った。その結果，雨季と乾季による差および流域内地質が，水質形成に大きな影響を及ぼしている可能性が高いことを示した。

第3章では，コンドリリ河川の水生植生の時空間分布特性について現地観測を中心に検討した。植生に関しても，雨季と乾季の別で顕著な差が観測された。また河川水の栄養塩濃度と植生現存量に相関が高いことが分かった。

第2章と第3章においては，アンデス高地の氷河下流河川域という特徴的な現場における現地観測により，希有な調査データを取得した。さらに，水環境要素である水質と植生に関する解析を行い，そこにおける水環境特性を示したことで，高標高地域の河川環境研究の進展に寄与する有用な成果が得られた。

第4章では，対象流域における水質と植生現存量についての予測解析モデルを構築した。本研究のモデル化の特徴は，水質と植生の相互作用を考慮したことである。すなわち，植生（主として沈水植物）の成長で水中の栄養塩を吸収し，枯死により栄養塩が回帰する過程を考慮した。その結果，河川水の栄養塩濃度の時空間分布特性と水生植生現存量を，概ね表現できる解析方法を構築することができた。

第5章では，コンドリリ川の植生と水質環境についての将来展望計算を行った。対象年代は，現在から約25年後の2039年とした。この将来期間においては，降水量および氷河からの融解水量が変化するため，河川流量も変化する。その影響により，植生および水質に影響が見られるという結果が得られた。

第4章と第5章における成果は，今後の対象地域における水道水源としての水質管理に寄与しうるものであり，工学的に有用な知見が得られたと考えられる。

以上より，本論文における研究成果は，熱帯氷河下流河川という特殊な河川環境に関する重要な知見を導出することができ，陸水学分野の発展に寄与するものであり，下流都市における水源環境管理に寄与しうる水工学的に重要な成果が得られたと判断される。

よって、本論文は博士(工学)の学位論文として合格と認める。