# GIS-BASED MULTI-CRITERIA DECISION MAKING UNDER SILICA SATURATION INDEX (SSI) FOR SELECTING THE BEST DIRECT USE SCENARIOS FOR GEOTHERMAL RESOURCES IN CENTRAL AND SOUTHERN RIFT VALLEY, KENYA

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論文題名：**GIS-BASED MULTI-CRITERIA DECISION MAKING UNDER SILICA SATURATION INDEX (SSI) FOR SELECTING THE BEST DIRECT USE SCENARIOS FOR GEOTHERMAL RESOURCES IN CENTRAL AND SOUTHERN RIFT VALLEY, KENYA** (ケニア中央および南部リフトバレーにおける地熱直接利用のベストシナリオ選択のためのシリカ飽和指数（SSI）に基づく GIS による意思決定手法)

区　　分：甲

論 文 内 容 の 要 旨

Geothermal energy is ubiquitous in the earth's crust, and its utilization has increased rapidly recently, anchored on its primary merits of low carbon emissions, renewability, and reliability. Using renewable energies is one of the fundamental strategies for decarbonizing the energy sector. The primary aim is to mitigate global warming by limiting global temperature rise to 2°C by 2100, as stipulated in the Paris Agreement of 2015. The utilization of geothermal energy is conventionally categorized into two major classes: the production of electricity (indirect use) and heating (direct use). Electric generation involves the use of steam and hot brine at temperatures ranging from 120 – 200°C, while thermal uses utilize hot brine at 30 – 150°C. Using geothermal resources to meet thermal needs such as heating water for bathing, horticultural greenhouse warming, residential/space heating, aquacultural pond heating, and industrial heating is defined as the direct use (DU) of geothermal energy. Direct use (DU) of geothermal energy is site-specific and majorly dictated by economics. Even with the availability of high enthalpy geothermal fluids, DU could still be curtailed by fluid pH, salinity, and silica content. Selecting economically viable best direct use (DU) scenarios for a given geothermal resource needs meticulous matching of geothermal resource characteristics to the nearby economic activities and local infrastructure. Silica saturation index (SSI) analysis should also be factored in to avoid silica scaling of DU facilities and reinjection well. There is a lack of a visual framework for incorporating all the necessary criteria for selecting the best DU scenarios, hence the motivation of this research. The current study employed a GIS-based multi-criteria decision-making (MCDM) method: a hybrid of the analytical hierarchy process (AHP) method with the weighted aggregated sum product assessment (WASPAS) method. The model was validated with existing DU case studies to gauge its ability to predict suitable utilization methods. There was a good match between the model's selection and existing case studies implicating the synergistic merger of GIS-based MCDM methods and SSI as a robust tool for planning and carrying out the feasibility study for DU of geothermal energy.

The outcome of this research will contribute to the overall understanding of selecting the best direct-use scenarios for each geothermal resource based on its fluid characteristic, local economic activities, and enabling local infrastructure. The study also characterizes high, medium, and low enthalpy geothermal resources, with or without productive deep wells or hot springs. The contents of the dissertation consist of six chapters below:

Chapter 1 Introduces the background of the study, the introduction of direct use of geothermal energy in high and low enthalpy geothermal resources, the geothermal status in Kenya. This chapter describes the research objectives and methodology.

Chapter 2 reviews geothermal state-of-the-art methods of classifying geothermal resources according to geology, temperature, and developmental status. Also reviewed in the chapter are the multi criteria decision making (MCDM) methods, criteria weighting, 2D inverse distance weighted and ordinary kriging interpolation methods of point vector data. Provided herein are brief reviews of the relevant prior works on geographic information systems (GIS), remote sensing (RS) of satellite images for land use classification, and location selection. Additionally, the innovative concept of enhancing silica solubility for moderately to highly alkaline geothermal resources by raising pH above 8.5 is presented.

Chapter 3 introduces the procedures of using MCDM methods in QGIS are expounded on, where the specific MCDM methods being (AHP-WASPAS hybrid) are outlined. The reasons and the procedures of selecting the 2D interpolation methods. Remote sensing, creation of criteria map layers and rasterization of vector data are given. Finally, the chapter summarizes the model for selecting the best use scenarios.

Chapter 4 expounds on the novel method of identifying and characterizing high enthalpy geothermal resources for direct use. The chapter analyzes six high enthalpy geothermal resources in central and southern Kenyan Rift Valley: Menengai, Elementaita, Eburru, Olkaria, Longonot and Suswa. The heat demands at the Olkaria, Eburru, and the Menengai geothermal fields were 180 MWt, 650 MWt, and 2050 MWt, respectively. Hence, Menengai and Eburru geothermal fields have more heat demands than Olkaria, while Olkaria has more volumes of disposable steam and brine compared to them.

Chapter 5 focuses on selecting geothermal resources in medium to low enthalpy geothermal resources with no deeper wells. The chapter identifies the significant role hot springs play by providing warm to hot fluids for direct use. The chapter expounds on hydrogeochemistry analysis of hot spring water and the use of resultant data to do exergetic classification of medium to low enthalpy geothermal resources in Kenya. Finally, the chapter selects best direct use scenarios for hot spring using GIS-based hydrogeochemistry data and economic enabling factors near the geothermal resource. The hot springs were discovered to provide approximately 275 MWt of heat, which is significant for direct usage.

Chapter 6 reviews all the direct use case studies in Kenya and tries to use them to validate the GIS-based MCDM selection model introduced in this study. The validation identified some case studies in high suitability areas while others were in areas classified as medium suitability. Even though those case studies that coincided with high suitability locations were financially viable, their establishment did not consider the results of the current study. The rest are of smaller scale and not economically sustainable.

Chapter 7 summarizes the overall conclusions and recommends future work optimizing geothermal resources in Kenya for direct use.