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ISÓTOPOS ESTÁVEIS DE ÁGUA NA PESQUISA EM IRRIGAÇÃO

CÉSAR DE OLIVEIRA FERREIRA SILVA[1]

[1] Laboratório de Recursos Hídricos e Isótopos Ambientais, Centro de Estudos Ambientais, Universidade Estadual Paulista (UNESP), Avenida 24 A,1515, CEP 13506-900 Rio Claro, São Paulo, Brasil, cesar.of.silva@unesp.br.

1 RESUMO

Essa nota científica apresenta a conceituação e aplicações das técnicas isotópicas para pesquisa e desenvolvimento em irrigação, especialmente no contexto de escassez hídrica. Destaque é dado aos métodos Keeling Plot e Isotopic Mass Balance (IMB). A nota traz conceitos e termos elementares aplicadas a problemas reais na pesquisa em irrigação, bem como reflexões sobre os elementos das diferentes modelagens e suas aplicações, e perspectivas sobre os usos presentes e futuros destas técnicas.

Keywords: hidrologia, isótopos de água, agricultura, ensino, pesquisa

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STABLE WATER ISOTOPES IN IRRIGATION RESEARCH

2 ABSTRACT

This scientific note presents the conceptualization and applications of isotopic techniques for irrigation research and development, especially in the context of water scarcity. The Keeling plot and isotopic mass balance (IMB) methods are highlighted. The note provides elementary concepts and terms applied to real problems in irrigation research, as well as reflections on the elements of the different models and their applications and perspectives on the present and future uses of these techniques.

Keywords: hydrology, water isotopes, agriculture, teaching, research

3 INTRODUCTION

Efficient management of water resources in agriculture has become a critical challenge in the face of increasing demand for food and increasing water scarcity. Irrigation represents the main consumer of freshwater in several countries and requires innovative solutions and increasingly accurate monitoring tools to ensure its sustainability (Silva, 2023). In this context, the application of isotopic techniques has emerged as a promising approach to study and optimize water processes in agricultural systems.

Isotopic techniques allow us to track the path of water in the environment on the basis of the isotopic signatures of elements, especially the stable isotopes of oxygen ($\delta^{18}O$) and hydrogen ($\delta^{2}H$). These isotopes provide detailed information about the origin, movement and evaporation of water in soil and plants. By applying these methods to irrigation, it becomes possible to

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assess water use efficiency, understand evaporation losses and identify the behavior of different water management strategies.

This scientific note aims to present the fundamentals and practical applications of isotopic techniques in irrigation research, with a special focus on Keeling methods. Plot and Isotopic Mass Balance (IMB). Both methods offer specific advantages for the analysis of water processes at the field scale. In addition to exploring fundamental concepts and associated terminologies, the article proposes reflections on the challenges and opportunities of using these tools in different agricultural scenarios.

4 ISOTOPIC TERMINELY AND TECHNIQUES

The use of stable isotopes in hydrological studies involves understanding fundamental terms and concepts. Isotopes are variants of the same chemical element that differ in the number of neutrons while maintaining similar chemical properties. In the case of water, the most commonly used isotopes are "deuterium (δ^2H) and oxygen ($\delta^{18}O$) The isotopic ratio of these species is expressed in delta notation (δ) compared with an international standard (VSMOW – Vienna Standard Mean Ocean Water).

The isotopic techniques used in irrigation studies aim to identify changes in the isotopic composition of water due to physical processes such as evaporation, percolation and transpiration. Analysis of the isotopic signatures of water collected at different points (irrigation water, soil, plants and the atmosphere) allows us to infer the dominant processes of water loss or redistribution in the system. In agricultural environments, these techniques help to assess the efficiency of irrigation methods such as drip, sprinkler or furrow irrigation.

Among the available techniques, two stand out for their applicability in the field and for providing quantitative interpretations of water processes: the Keeling method plot, which allows estimation of the isotopic composition of evaporation sources, and the isotopic mass balance method, which evaluates isotopic fractionation in open or closed systems. Both techniques complement each other, allowing a more complete diagnosis of water use and loss processes in irrigated agricultural systems.

5 USE OF THE KEELING PLOT TECHNIQUE IN IRRIGATION

Keeling method plots are widely used to identify the isotopic signatures of sources that contribute to a mixture, such as the evaporation of water from soil or vegetation. The technique is based on the linear relationship between the isotopic ratio of the mixture and the inverse of the concentration of the compound (in this case, water vapor). Extrapolation of the regression line allows the determination of the isotopic signature of the dominant evaporative source, which is a valuable tool for studies in irrigated environments.

In irrigation research, the Keeling plot allows estimation of the contribution of soil water evaporation to atmospheric vapor, distinguishing it from plant transpiration. This is essential for differentiating water losses that do not contribute to plant growth and are therefore not desirable. When applied in conjunction with meteorological sensors and field collections, this method helps to quantify evaporation losses under different irrigation systems and managements. Yuan *et al. (2020) proposed methods based on the* Keeling plot to estimate the isotopic composition of ambient water vapor, which improved the accuracy of estimates in terrestrial ecosystems.

6 USE OF MASS BALANCE TECHNIQUE IN IRRIGATION

Isotopic mass balance (IMB) is a quantitative approach to analyze the isotopic evolution of water in a system. This method is based on the principle of conservation of mass and takes into account the isotopic fractionation effects associated with evaporation. In the context of irrigation, IMB allows estimation of the fraction of applied water that is lost through evaporation and transpiration, in addition to providing support for optimizing water application. Putman *et al.* (2024), for example, evaluated the US National Water Model, revealing contributions from agricultural irrigation not represented in river runoff, through isotopic analyses. Bisht *et al. (2024) evaluated* hydrogeochemical processes for use in irrigation and identified potential sources of nitrate contamination in groundwater via stable nitrogen isotopes.

A typical field application of IMB involves collecting water samples from different compartments (e.g., applied water, soil water at varying depths, and water transpired by plants) and analyzing them via isotopes. From this, it is possible to construct balance equations that describe the transformations undergone by water in the irrigated system. This allows researchers to identify critical loss points and assess the efficiency of irrigation strategies. Vallet-Coulomb *et al.* (2017) combined stable isotope and chloride data to infer irrigation return flows in a Mediterranean aquifer, highlighting the importance of isotopic techniques in groundwater resource management.

The integration of the IMB with other data, such as soil moisture, electrical conductivity and meteorological information, broadens its applicability and increases the robustness of the conclusions. This technique has been successfully used in crops such as corn, rice and sugarcane, contributing to the improvement of irrigation management in different climatic and edaphological contexts. Zhang, Wang and Liu (2022) used stable isotopes to determine the ideal application of irrigation water in a corn field, contributing to more efficient agricultural practices.

7 FINAL CONSIDERS

Isotopic techniques, especially the Keeling plot and isotope mass balance, offer powerful tools for analyzing hydrological processes in irrigation systems. The application of these methods contributes significantly to understanding water flows, identifying losses and increasing water efficiency, which are essential elements in the face of water scarcity. Advances in sensing and isotope analysis technologies promise to further expand the possibilities of using these tools, integrating them into precision management in irrigated agriculture.

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