

Water balance of Huacachina Oasis, Peru

Balance hídrico del oasis de Huacachina, Perú

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Citar como: Noa-Yarasca, E. and Noa-Miranda, G. (2024). «Water balance of Huacachina Oasis, Peru». *South Sustainability*, 5(2), e101.
DOI: 10.21142/SS-0502-2024-e101

Artículo recibido: 9/4/2024
Revisado por pares
Artículo aceptado: 1/7/2024



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ABSTRACT

The Huacachina oasis, on Peru's south-central coast, is an important tourism hotspot, driving economic activity in the Ica region. However, its natural sustainability has been compromised by aquifer overexploitation, leading to a decline in the water table. Currently, it is grappling with water recharge challenges, and has been resorting to methods such as recharging water from wells. Despite its importance, there have been few studies of the water balance at the Huacachina oasis. The aim of this study was to investigate the hydrological balance of the oasis, scrutinizing both water losses and gains, including evaporation, infiltration and inflows. Over a 72-hour period, precipitation, water level fluctuations and inflow rates were recorded and validated. Evaporation was indirectly computed using the Penman method, which is known for its efficacy. The oasis's storage capacity was assessed using detailed bathymetric and topographic surveys. The study identified the lowest bottom elevation at 401.488 m.a.s.l., the highest at 404.194 m.a.s.l., and a storage capacity of 35,813 m³. Our results showed precipitation had no impact on water supply, with the main source being well water pumped from underground. Water losses were due mainly to evaporation and infiltration. Daily evaporation averaged 7.7 mm, while the infiltration rate stood at 0.55 mm/hr. Infiltration exceeded evaporation by 1.7 times (63.4% vs. 36.6%). A water imbalance of 11.5 % was identified, with water inflows exceeding outflows, probably due to leaks in water and sewage systems. Unlike previous research, this study provides a detailed temporal analysis of Huacachina oasis water dynamics; however, in the future additional research will be required to address limitations. Our study also emphasizes the need to explore hidden water sources (leaks in water and sewage networks), in order to address improved oasis management and the effects of climate change, and to ensure sustainability.

Keywords: Huacachina oasis, water balance, hydrological balance, evaporation, infiltration

RESUMEN

El oasis de Huacachina, en la costa centro-sur del Perú, es un importante destino turístico que impulsa la economía regional de Ica. Comprometida su sostenibilidad por el descenso del nivel freático debido a la sobreexplotación del acuífero, actualmente enfrenta desafíos de recarga de agua. A pesar de su relevancia, los estudios sobre su balance hídrico son escasos. Este estudio investiga el balance hidrológico del oasis, al examinar los principales ingresos y salidas de agua. Durante 72 horas, se registraron precipitaciones, fluctuaciones del nivel del agua y flujos de entrada. La evaporación se calculó con el método de Penman y la capacidad de almacenamiento se determinó con levantamientos batimétricos y topográficos. La precipitación no contribuyó al suministro del oasis; la transferencia de agua de pozo fue la principal fuente de ingreso. Las pérdidas/salidas de agua se atribuyeron principalmente a la evaporación y la infiltración, con una evaporación diaria promedio de 7,7 mm y una tasa de infiltración de 0,55 mm/h. La infiltración superó la evaporación en 1,7 veces (63,4 % vs. 36,6 %). Se detectó un desequilibrio en el balance hídrico del 11,5 %, con ingresos de agua superiores a los egresos, posiblemente debido a fugas en los sistemas de agua y alcantarillado que contribuyen al oasis de manera no visible. A diferencia de trabajos previos, este estudio ofrece un análisis diario de la dinámica hídrica del oasis, al proporcionar datos relevantes. Futuras investigaciones deben enfocarse en detectar flujos de agua no visibles (fugas en redes de agua y alcantarillado) y analizar escenarios de cambio climático para garantizar su sostenibilidad a largo plazo.

Palabras clave: Oasis de Huacachina, balance de agua, balance hídrico, evaporación, infiltración



Introduction

The Huacachina oasis, known locally as Laguna Huacachina, lies within the Ica desert, on Peru's south-central coast. It is one of a cluster of natural oases in the area, formed when elevated groundwater levels from the Ica Valley surface in the low depressions set amid the desert dunes (MPI, 2021; Negro, 2016). Today, Huacachina holds considerable importance in the Ica region as a prominent tourist destination, attracting many visitors and driving significant local economic activity (Carrión Elías, 2021; Gonzales Cervantes, 2014; Kingsmore, 2017; Toivanen, 2023).

Beginning in the 1930s, and peaking in the 1950s, the Huacachina oasis, once naturally sustained, began to decline due to the overexploitation of the Ica-Villacuri aquifer (ANA, 2012; MPI, 2021). By the late 1960s, there were approximately 780 groundwater extraction wells in the Ica-Villacuri valley, withdrawing an estimated 346 million cubic meters (MCM) of water annually, thereby surpassing the sustainable extraction volume, estimated at 252.99 MCM by the National Water Authority (Autoridad Nacional del Agua, ANA, 2003, 2012; Oré *et al.*, 2013). Despite this aquifer overexploitation, water levels in the oasis remained relatively stable, with only a slight decrease, until 1974. This was due, in part, to seepage from the irrigation waters of the valley contributing to the oasis (Gonzales Cervantes, 2014), as well as the shallow water table (ANA, 2003). However, continuing overexploitation subsequently led to a rapid decline in the water table region-wide, resulting in the alarming disappearance of several oases, including Huacachina, in 1978 (ANA, 2003; CIPUR, 1996; MPI, 2021). Subsequently, the Huacachina oasis was artificially replenished with water extracted from wells. By 2009, over 900 wells were documented, excluding unreported ones in the region (ANA, 2012; Gonzales Cervantes, 2014). During this period, approximately 543.15 MCM were extracted (Oré *et al.*, 2013). According to ANA (2017), from 2007 to 2009 water extraction averaged 385.5 MCM/year, surpassing sustainable levels and worsening the prospects for natural oasis recovery. By 2017, although extraction had decreased to around 231.6 MCM, the water table remained too low (ANA, 2017) for natural replenishment of the oasis.

Initiatives to restore and preserve the Huacachina oasis have involved both governmental agencies and civil society. These have included the creation of a water reserve in the «Rincón Grande» basin (northwest of the oasis) to replenish the oasis via filtration and/or pumping, as well as dredging its bed to enhance ecological balance and resilience (ANA, 2003; Gonzales Cervantes, 2014). However, these efforts have been sporadic and have not resulted in a sustainable long-term solution. Currently, the oasis receives varying amounts of well water based on volumes remaining after meeting the population's needs.

Despite the importance of the Huacachina oasis for tourism and the local economy in Ica, there has been no detailed assessment of its water resources (Oré *et al.*, 2013). Existing studies focus mainly on regional analyses, overlooking the oasis's local conditions (ANA, 2003). In this context, the aim of our study is to evaluate Huacachina's water balance, analyzing daily losses and gains (e. g., evaporation, infiltration and water inputs) in order to identify key mechanisms of water loss and determine the minimum water needs for oasis preservation.

Methodology

Huacachina Oasis: Study area & water level history

The Huacachina oasis, in Peru's Ica desert, was formed by rising waters from the Ica aquifer fed by underground flows (ANA, 2003; CIPUR, 1996). The oasis, located about 5 km southwest of Ica, is surrounded by a relatively dense urban area to the north, east and partially to the south, with palm trees, eucalyptus and American carob (known in Peru as «*huarango*») filling the remaining space (Figure 1). Urban settlements began forming in the 1890s (Gonzales Cervantes, 2014) and are now dominated by hotels for visitors (Toivanen, 2023). This growth has led to the installation of water and sewage systems, as well as recreational activities, altering the oasis's natural environment (ANA, 2003). In terms of climate, the region experiences minimal precipitation, averaging only a few millimeters annually. During peak rainfall months (December-March), the average barely reaches 3 mm, with negligible precipitation for the remainder of the year. Average monthly temperatures range from 24.0°C in February to 18.3°C in July (ANA, 2003, 2017). These elevated temperatures contribute to significant evaporation, averaging around 1500 mm annually (ANA, 2003).

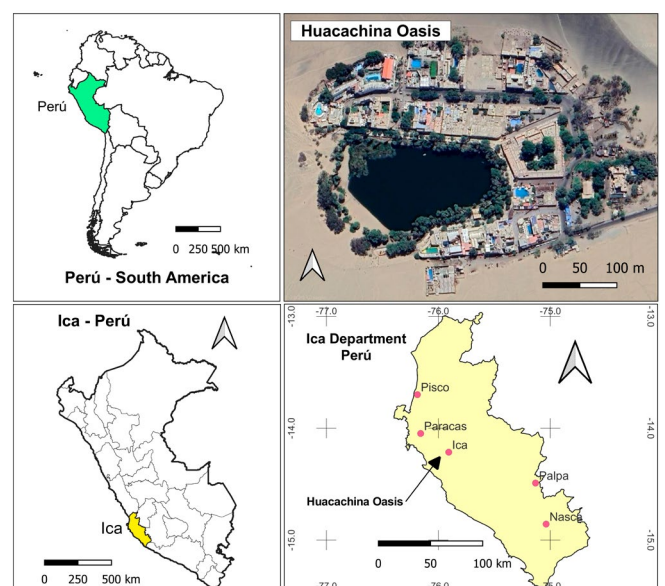


Figure 1. Study area map.

Once sustainable, the oasis has suffered water quantity and quality deterioration due to exploitation of the Ica aquifer (ANA, 2015; Mendoza-Carbajal, 2016; Peralta Roldan, 2019). Records dating back to the 1940s show a steady 0.9 cm/year decline up until 1974, followed by a rapid decrease, leaving the oasis almost dry by 1978 (Figure 2). This degradation coincided with the onset of groundwater exploitation in the 1930s, exacerbated by overexploitation in the 1960s and beyond, surpassing sustainable extraction levels (ANA, 2003; CIPUR, 1996). Subsequently, the oasis has relied on artificial maintenance through water allocation from wells managed by the Municipal Agency of Drinking Water and Sewerage of Ica (Empresa Municipal de Agua Potable y Alcantarillado de Ica, EMAPICA). However, since the agency's primary goal is to supply drinking water, water allocations for the oasis are irregular and non-mandatory. Thus, the oasis has undergone two stages, up to and beyond the year 1978: the first as a natural oasis, and the second as an artificially sustained body of water.

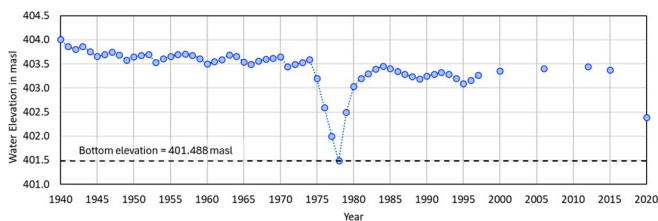


Figure 2. Historical annual average water depth of the Huacachina oasis, using data from CIPUR (1996), ANA (2003 and 2015). Post-2003 average water-depth data were estimated by outlining oasis surface areas in satellite images around journalistic report dates. These areas were converted to water levels using the study's hypsometric curve. Note: Post-1978 levels were affected by irregular artificial recharge.

Water balance components

The water balance study of the Huacachina oasis assessed inflows and outflows, adhering to the principle of mass conservation. It quantified the change in volume (ΔV) as the difference between incoming (well water transfer inputs [I_{tr}] and rainfall [I_{rain}]) and outgoing (evaporation [O_{ev}] and infiltration [O_{inf}]) volumes. The equation governing volume change over time (Δt) was as follows:

$$\Delta V = I_{tr} + I_{rain} - O_{ev} - O_{inf} \quad (1)$$

Fieldwork was conducted over a 72-hour period in late summer of 2022, in order to evaluate water balance components, with intermittent interruptions due to resource constraints and personnel safety measures. Precipitation, water level fluctuations and inflow rates were carefully recorded and validated. Precipitation was calculated using a standard rain gauge (TY4, 4.2 x 4.2 x 14 inches), featuring a funnel directing water into a graduated measuring tube marked in millimeters, with an accuracy of 0.25 mm. Water levels were meticulously measured using the Leica Flexline TS03 total station, equipped

with an electronic distance meter (EDM R500), precisely calibrated by the manufacturer for optimal performance (Absolute accuracy: 2", continuous: 3", diameter: 5"). Evaporation was estimated indirectly using the Penman method, which is renowned for its comprehensive efficacy (Jensen *et al.*, 2005; Zotarelli *et al.*, 2020).

The water balance of the oasis was analyzed over seven time periods, as detailed in Table 1. Field water level measurements from Period 3 (2/3/22 5:00) and Period 6 (3/3/22 5:00) served as checkpoints for validation. These checkpoints compared water levels determined through the water balance with *in situ* measurements, thereby ensuring result accuracy.

Table 1. Time periods for Huacachina Oasis water balance

Time Period	Start time	End time	Time step	Description
	m/d/yy h:mm	m/d/yy h:mm	number of hours	
1	3/1/22 5:00	3/1/22 21:00	16	Water output
2	3/1/22 21:00	3/1/22 23:00	2	Water output
3	3/1/22 23:00	3/2/22 5:00	6	Water input & output (checkpoint)
4	3/2/22 5:00	3/2/22 21:00	16	Water output
5	3/2/22 21:00	3/2/22 23:00	2	Water output
6	3/2/22 23:00	3/3/22 5:00	6	Water input & output (checkpoint)
7	3/3/22 5:00	3/3/22 21:00	16	Water output

Determining Huacachina Oasis storage capacity & characteristics

The oasis storage capacity was assessed via bathymetric surveys, employing precision equipment (total station and millimeter rulers). Detailed topographic measurements were conducted around the water body and processed using AutoCAD Civil 3D software, in order to determine bed configuration and calculate volume and surface area at different levels. This facilitated the creation of elevation-volume and elevation-surface area curves, thereby establishing maximum storage capacities.

Huacachina Oasis water loss components

Infiltration assessment of the oasis involved monitoring water level decline during fieldwork. By placing a millimeter ruler at the southern boundary, we conducted hourly measurements using topographic instruments. Data gathering was conducted daily from 5 a.m. to 9 p.m., taking into account resource constraints and personnel safety protocols.

Evaporation of the Huacachina oasis was determined utilizing the Penman method, a widely recognized and sophisticated approach. This method integrates various meteorological parameters, such as net radiation, air temperature, humidity, wind speed and water temperature, to provide a comprehensive assessment of evaporation (E) dynamics (Jensen *et al.*, 2005; Zotarelli *et al.*, 2020).

$$E = \frac{0.408 \Delta R_n + \gamma \frac{C_n}{T+273} u_2 (e_s - e_a)}{\Delta + \gamma(1 + C_d u_2)} \quad (2)$$

$$\Delta = \frac{4098 e_s}{(T+273.3)^2} \quad (3)$$

$$\gamma = 0.00163 \frac{P}{\lambda} \quad (4)$$

$$e_s = 0.611 e^{\frac{17.27 T}{T+273.3}} \quad (5)$$

Where R_n is the net solar radiation ($\text{MJ m}^{-2}\text{h}^{-1}$), T is the mean air temperature ($^{\circ}\text{C}$), u_2 is the wind speed (m/s), Δ is the slope of the saturation vapor pressure curve, e_s is the saturation vapor pressure at the air temperature (kPa), e_a is the vapor pressure for T (kPa) ($e_a = e_s R_H$), R_H is the relative humidity, γ is the psychrometric constant ($\text{kPa } ^{\circ}\text{C}^{-1}$), P is the atmospheric pressure (kPa), λ represents the latent heat of vaporization, given by ($\lambda = 2.5 - 0.0024 T_w$) (Majidi *et al.*, 2018), where T_w is the water temperature that can be computed by the modified Stefan & Preud'homme equation for Peru ($T_w = 4.18 + 0.63 T$) (Noa-Yarasca *et al.*, 2022; Stefan & Preud'homme, 1993). In addition, $C_n = 37.5$ for hourly calculations, and $C_d = 0.24$ for daytime and 0.96 for nighttime (Zotarelli *et al.*, 2020).

Hourly data on humidity, wind speed, and air temperature for the assessed days were sourced from the official websites of the National Meteorology and Hydrology Service of Peru (Servicio Nacional de Meteorología e Hidrología del Perú, Senamhi, <https://www.senamhi.gob.pe/?p=estaciones>) and Weather Spark (The Weather Year Round Anywhere on Earth, <https://weatherspark.com/y/22218/Average-Weather-in-Ica-Peru-Year-Round>). Solar radiation data was only available at the daily level, and was therefore downscaled to hourly using the Kaplanis approach (Kaplanis, 2006; Noa-Yarasca *et al.*, 2023). This method represents daily radiation as a cosine function constrained by sunrise and sunset and adjusted for the day (Equation 6).

$$h_{ij} = a + b \cos\left(\frac{2\pi t_i}{24}\right) ; t_{sr} < t_i < t_{ss} \quad (6)$$

Where h_{ij} is the hourly solar radiation, i is the hour index, j is the Julian day index, t_i is the time in hours, and a and b are coefficients specific to each site and day. These coefficients are determined by solving Equation (7) with boundary conditions, ensuring that integration from sunrise (t_{sr}) to sunset (t_{ss}) equals daily solar radiation (R_{nj}), and solar radiation is zero at sunset ($h_{ij} = 0$ for $t_i = t_{ss}$).

$$R_{nj} = \int_{t_{sr}}^{t_{ss}} h_{ij} dt \quad (7)$$

Huacachina Oasis water recharge components

During the fieldwork phase, a calibrated rain gauge was strategically placed at a height of 0.80 m above ground level, specifically on the western edge of the oasis. Situated in an unobstructed area, it facilitated precise measurement of precipitation events. During the three-day assessment, recharge occurred from 11 pm to 5 am , aligning with Huacachina's low water demand hours. Water was pumped from the adjacent well to the oasis at a rate of approximately $12 \text{ liters per second}$, managed by EMAPICA's trained personnel. Additionally, around 120 m^3 of water from the reservoir were introduced.

Results

Huacachina Oasis storage & features

Bathymetric surveys of the oasis and the surrounding topography revealed the lowest point in the oasis bed at 401.488 meters above sea level (m.a.s.l.), while the water level recorded during the surveys was 404.065 m.a.s.l. The maximum water level determined, at 404.194 m.a.s.l. , is constrained by the introduction of resort infrastructure, including sidewalks, steps and gardens. Figure 3 shows the hypsometric curve correlating water volume (V) and water level, alongside the corresponding water surface area (A). The curves were fitted using second-order polynomial equations (All showing $R^2 = 0.99$). The equations are as follow:

$$V = 2937.6 h^2 + 5383.8 h - 265.5$$

$$A = -338.9 h^2 + 6402.3 h + 5607.7$$

$$V = 1 \times 10^{-4} A^2 - 0.932 A + 1457.1$$

Where h represents water depth in meters, and V and A in m^3 and m^2 , respectively. The equation for surface area was fitted in the water depth range of 0.50 to 2.76 m . Within elevation limits, the maximum storage volume was found at about $35,813 \text{ m}^3$, with a maximum water surface area of about $20,450 \text{ m}^2$.

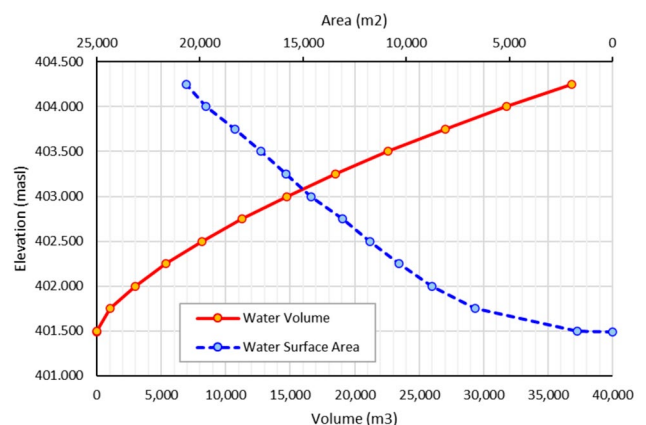


Figure 3. Hypsometric curve illustrating water volume and surface area vs. elevation in the Huacachina oasis.

Huacachina Oasis water losses

The water level dropped by 15.5 mm, 16.0 mm and 16.0 mm, respectively, over the three assessed days (Figure 4a). According to the hypsometric curve, these declines corresponded to water volume losses of 317.7 m³, 328.2 m³ and 328.2 m³, accounting for both infiltration and evaporation.

The evaporation results revealed pronounced water decline during the 8 am to 5 pm period, correlating with high temperature and solar radiation and low evaporation ratios in the remaining hours of the day (Figure 4b). Between 5 am and 9 pm, evaporation volumes were 139.3 m³, 154.1 m³ and 152.9 m³. Calculation details are provided in the supplementary materials accompanying this article.

Infiltration through the oasis bed was determined by subtracting evaporation from the total volume of water decline observed over the measured interval. Thus, during the assessed period from 5 am to 9 pm, the estimated infiltration volumes were 178.4 m³, 174.2 m³ and 175.6 m³, averaging a rate of 0.55 mm/hr. This ratio was then applied to estimate water losses during the unrecorded period (9 pm to 5 am the next day), resulting in 24-hour infiltration volumes of 267.6, 261.3 and 263.4 m³ (Table 2 summarizes the calculations). Notably, evaporation accounted for an average of 36.6% of water losses during the evaluated period.

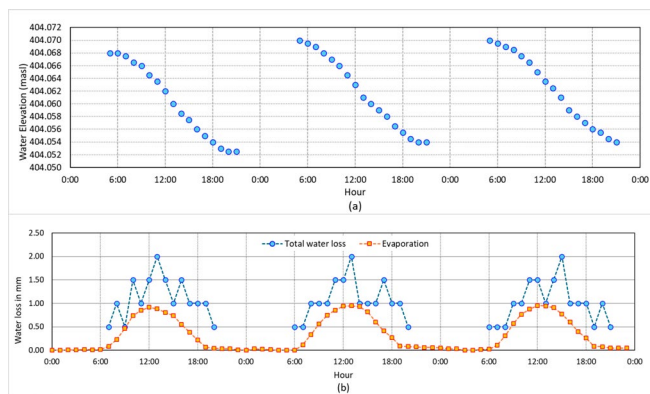


Figure 4. (a) Water elevation decline, (b) Total water loss and evaporation in mm.

Table 2. Huacachina oasis evaporation and infiltration analysis

Day	Water Elev. drop (16 hr) mm	Avg. Water Surf. Area (16 hr) m ²	Water Vol. loss (16 hr) m ³	Evaporation Water loss (16 hr) m ³	Infiltration Water loss (16 hr) m ³	Water drop Infiltration (16 hr) mm	Infiltration rate mm/hr	Water drop Infiltration (8 hr) mm	Infiltration Water loss (8 hr) m ³	Infiltration Water loss (24 hr) m ³	Evaporation Water loss (8 hr) m ³	Infiltration+Evap Water loss (24 hr) m ³	Evap. Percent. %
Day1	15.5	19833.9	317.7	139.3	178.4	8.99	0.56	4.50	89.2	267.6	2.20	409.1	34.6%
Day2	16.0	19840.6	328.1	153.9	174.2	8.78	0.55	4.39	87.1	261.3	5.22	420.4	37.9%
Day3	16.0	19842.7	328.1	152.5	175.6	8.85	0.55	4.43	87.8	263.4	4.55	420.5	37.3%

Huacachina Oasis water intake

During the evaluation period, zero precipitation was registered, confirming the region's arid characteristics and scarce rainfall (ANA, 2003; Valle Basto, 2000). The recharge rate was 12 liters per second over six hours, resulting in a daily supply volume of 259 m³. Additionally, the oasis received around 120 m³ from the drinking water reservoir, totaling an average daily intake of around 379 m³.

Water balance

The water balance results are presented in Table 3. During **period 1**, there was no water inflow. The decrease in oasis volume was primarily due to infiltration and evaporation. Infiltration volume was determined by deducting evaporation from the volume loss by water level decline. Initial (V_i) and final (V_{i+1}) volumes were determined by substituting the *in situ* water elevations (E_i, E_{i+1}) in the water depth-volume equation. In **period 2**, infiltration volume was computed using an infiltration rate of 0.55 mm/hr. The final volume (V_{i+1}) was determined through balance (eq.1), followed by establishing the final water elevation (404.0514 m.a.s.l.) using the water depth-volume equation. In **period 3** (first checkpoint), balance components were determined similarly to period 2, with water inflow included. The final elevation was 404.0685 m.a.s.l., compared to the *in situ* measurement of 404.0705 m.a.s.l., revealing a discrepancy of approximately 2 mm, equivalent to 39.7 m³ (10.5%). In **period 4**, the water balance began using the *in situ* water elevation measurement, rather than the one calculated in the preceding period. Employing a methodology akin to that used for period 1, infiltration volume was determined by deducting evaporation from the volume lost due to water level decline. The initial and final volumes were derived by substituting the *in situ* elevation measurements into the water depth-volume equation. In **period 5**, infiltration volume was computed using the infiltration rate of 0.55 mm/hr over two hours. The final water volume was determined through water balance (equation 1), with subsequent calculations of the water depth and elevation (404.0533 m.a.s.l.). In **period 6** (second checkpoint), infiltration was calculated at 0.55 mm/hr over six hours. The final water volume

was determined by water balance, and the water depth by using the elevation-volume equation, resulting in a water elevation of 404.0691 m.a.s.l. A comparison with the *in situ* measurement (404.0715 m.a.s.l.) revealed a 2.4 mm discrepancy, equal to 47.6 m³ (12.6%). In **period 7**, components were determined as in period 4.

Checkpoints indicate that output volumes exceed input volumes in the Huacachina oasis, with an average discrepancy of 11.5%. These differences may stem from unidentified recharges, possibly due to leaks in the deteriorated urban water and sewerage system, as well as hotel pools. In addition, water intake from the nearby Cochabamba sewage treatment plant, located 120 meters away and 20 meters above the oasis level, is another possible factor. Previous studies have also documented leaks due to water misuse and degradation of the water and drainage service system in the Huacachina oasis (ANA, 2003).

Taking into account infiltration and evaporation rates, the oasis requires approximately 380 m³ to maintain the water level at about h = 2.50 m. However, this volume is subject to climatic and oasis conditions. In the early 20th century, natural oasis volumes were higher; for instance, in 1915, reports indicated a water surface area of 25,200 m², projecting a volume of around 41,400 m³ (Gonzales Cervantes, 2014).

Discussion

This research underscores the lack of natural recharge in the Huacachina oasis. Despite March falling within the summer season, traditionally bringing some rainfall to the Ica region, precipitation was absent during the study period, confirming a significant limitation in the oasis's water resource. This aligns with the desert climate of the region, as noted in previous studies (ANA, 2003).

Our study found daily water losses due to a combination of infiltration and evaporation, with 63.4% attributed to infiltration and 36.6% to evaporation. This means infiltration exceeded evaporation by 1.7 times.

While previous annual water balance assessments suggested that infiltration rates were approximately 3.5 times that of evaporation (ANA, 2003), they lacked direct measurements of water level decline and the relationships between water level, volume and surface area. Instead, these assessments considered factors such as average well water endowment and average annual evaporation. In contrast, our study provided precise measurements, highlighting the importance of direct data collection for accurate water loss assessment.

The water balance shows an average imbalance of 11.5%, where water inflows exceed outflows. In the absence of other visible sources of water inflow to compensate for this imbalance, it is assumed that these flows stem from leaks in the drinking water and sewerage network system, as well as from hotel pools, and possibly from the nearby wastewater treatment plant. In addition, locals reported deterioration in these services due to their age. This aligns somewhat with ANA's findings, revealing water losses of up to 38.9% in the Huacachina oasis, primarily stemming from population misuse and leaks in water and sewerage infrastructure (ANA, 2003, 2012). It is important to note that the percentages of water balance components identified in this study may vary depending on the season and environmental conditions at the oasis. For instance, seasonal temperature and solar radiation fluctuations affect evaporation rates, and may decrease markedly in winter. Infiltration rates may moderately vary with water levels, in accordance with Darcy's law; however, utilizing the hypsometric curve derived from this study, adjustments to the oasis water balance can be made.

Regarding the natural recharge options of the oasis, the prospects are limited. The nearby Ica River, the primary source of surface water, exhibits intermittent flow, peaking from January to March, and little or no flow from June to August (ANA, 2012, 2017; Valle Basto, 2000). Primarily, this water resource serves the agricultural requirements of the Ica Valley, where demand consistently

Table 3. Water balance of the Huacachina oasis. The numbers in blue correspond to elevations measured *in situ*

Time Period	Time step Δt hr	Elevation (in-situ) E _i masl	Water depth h _i m	Water Surf. Area A _i km ²	Water Volume V _i m ³	Well Water Inlet I _{tr} m ³	Rainwater Inlet I _{rain} m ³	Evaporation Water loss O _{ev} m ³	Infiltration Water loss O _{inf} m ³	Water Volume V _{i+1} m ³	Water depth h _{i+1} m	Elevation (Calc) E _{i+1} masl	Elevation (in-situ) E _{i+1} masl	Difference in Elev. ΔE mm
1	16	404.0680	2.5800	19,869.8	33,178.5	0	0	139.3	178.4	32,860.9	2.5645		404.0525	
2	2	404.0525	2.5645	19,797.6	32,860.9	0	0	1.39	21.8	32,837.7	2.5634	404.0514		
3	6	404.0514	2.5634	19,792.3	32,837.7	379.2	0	1.81	65.3	33,149.8	2.5805	404.0685	404.0705	2.0
4	16	404.0705	2.5825	19,881.4	33,229.9	0	0	153.9	174.2	32,901.8	2.5665		404.0545	
5	2	404.0545	2.5665	19,806.9	32,901.8	0	0	2.69	21.79	32,877.3	2.5653	404.0533		
6	6	404.0533	2.5653	19,801.3	32,877.3	379.2	0	3.63	65.3	33,187.5	2.5811	404.0691	404.0715	2.4
7	16	404.0715	2.5835	19,886.1	33,250.5	0	0	152.5	175.6	32,922.4	2.5675		404.0555	

exceeds supply, resulting in aquifer overexploitation. Furthermore, over 92% of the water usage rights for the Ica River are allocated to farmers (ANA 2012). Consequently, the Huacachina oasis faces a challenging and uncertain future, due to the scarcity of natural water resources, and to aquifer depletion.

Despite meticulous data collection and processing, hydrological outcomes may vary slightly due to inherent uncertainties. Factors such as input data, equations and parameters contribute to such uncertainty. Therefore, further assessment is recommended of the water balance of the Huacachina oasis under different conditions, in order to ascertain the resource requirements for maintenance and preservation. Additionally, identifying and integrating uncontrolled water inputs into a refined hydraulic balance is advised. Given projected temperature increases resulting from climate change, evaluating the water balance within future climate scenarios will be crucial for informing adaptation plans.

Conclusion

This study analyzed and evaluated the hydrological dynamics of the Huacachina oasis, a popular tourist attraction in Ica, Peru, and an economic driver for the local region. After reaching utter depletion in 1978, the Huacachina oasis is now artificially maintained through the supplying of well water in varying amounts. The water balance assessment encompassed important components of water inflows and outflows, including precipitation, external water replenishment, infiltration and evaporation. Conducted over a 72-hour period, the study encountered sporadic interruptions due to resource constraints, during which a variety of *in situ* measurements were conducted. These included bathymetric and topographic surveys of the oasis and its environs, alongside continuous monitoring of water level fluctuations and precipitation. Evaporation rates were derived indirectly through the Penman method. Data on the volume of water entering the oasis was sourced from the overseeing entity of the nearby well.

This study also identified key physical features of the Huacachina oasis, including its minimum bed level at 401.488 m.a.s.l. and maximum storage level at 404.194 m.a.s.l., constrained by urban structures and resulting in a maximum storage volume of 35,813 m³. The oasis relied primarily on pumped well water for its water supply, given the absence of precipitation during the study period. Our

analysis estimated an infiltration rate of 0.55 mm/hr and found that infiltration exceeded evaporation by 1.7 times. Overall, the water balance displayed an average imbalance of 11.5%, where water inflows exceeded outflows. In the absence of observable sources compensating for this discrepancy, it was hypothesized that these additional flows stemmed from drinking water and sewerage system leaks.

Unlike previous studies conducted on an annual time step, our research adopted a daily temporal framework to evaluate infiltration, evaporation and unaccounted losses within the oasis, thereby yielding significant insights. It is important to note that these findings may vary across different seasons and under varying oasis conditions. Future studies should focus on identifying non-visibly detectable water inflows into the oasis, in order to safeguard both its quantity and quality. Moreover, analysis of climate change scenarios will be essential, in order to develop adaptation strategies and ensure the long-term sustainability of the oasis.

Acknowledgments

The authors of this study acknowledge the support of the NVBC company, which provided bathymetric and topographic data.

Funding sources

Logistical support and funding for this study were received from the ADES-Perú agency (Grant No. 0001).

Author contributions

ENY conceptualized the research project and literature review, with ENY and GNM both conducting data searches. GNM conducted the evaporation calculations, while ENY conducted the water balance and other calculations. Both ENY and GNM prepared the tables and figures. ENY reviewed the calculations, drafted the manuscript and finalized the edits.

Conflicts of interest

The authors have no conflicts of interest to declare.

Data availability

Data collected during this study are available upon request from the corresponding author.



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