

Physiological strain and recovery-time modelling in amateur runners exposed to severe heat stress in Natitingou, northern Benin

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Abstract

Endurance running during the hottest hours combines high metabolic heat production with intense solar radiation and elevated air temperature. This study quantified physiological strain and modelled the recovery time required for amateur runners in Natitingou, northern Benin, to return below a Physiological Strain Index (PSI) of 3. Eighty-four runners aged 18–45 years completed 45 min of running at 70% of maximal aerobic speed between 12:00 and 15:00 from February to April. Heart rate and tympanic temperature were measured before exercise, immediately after exercise, and every 5 min during 30 min of shaded recovery. Mean wet-bulb globe temperature (WBGT) was $29.8 \pm 1.6^{\circ}\text{C}$, mean end-exercise PSI was 7.1 ± 1.0 , and 54.8% of participants reached $\text{PSI} \geq 7$. Mean time to $\text{PSI} < 3$ was 20.2 ± 4.8 min with immediate water intake ≥ 500 mL and 24.5 ± 4.7 min with intake < 250 mL. A multiple linear regression model including WBGT, end-exercise PSI, maximal aerobic speed, age and fluid intake explained 66.8% of recovery-time variability, with a mean absolute error of 2.4 min. Each 1°C increase in WBGT added 1.55 min to predicted recovery time, while low fluid intake added 4.46 min. These findings support avoiding the hottest training hours and formalising shaded, hydrated recovery periods.

1. Introduction

Prolonged physical exercise in hot environments increases metabolic heat production, body temperature and cardiovascular demand. Among amateur runners in tropical settings, training during periods of intense solar radiation, combined with often irregular hydration, substantially increases the risk of heat exhaustion and exertional heat stroke. To assess this overall burden, Moran, Shitzer and Pandolf (1998) developed the Physiological Strain Index (PSI), a dimensionless index combining the rise in core temperature and heart rate on a standardised scale from 0 to 10. International recommendations for exercise in the heat emphasise acclimatisation, adequate rehydration and strategic adjustment of training schedules as key protective measures (Racinais et al. 2015). Casa et al. (2015) likewise stress the importance of early recognition of heat stress and rapid cooling of athletes who develop signs of hyperthermia. A major field concern is that heart rate recovers much more rapidly than core temperature after exercise cessation. This may create a misleading impression that physiological equilibrium has been restored, in relation to the cardiovascular drift mechanism described by Wingo et al. (2012). Consequently, management of rest periods requires a combination of environmental monitoring, access to shade, water intake and a rigorous structure for recovery intervals (Racinais et al. 2023). In northern Beninese cities such as Natitingou, which experience a Sudanian climate with very high daytime temperatures during the dry season, running sometimes takes place during the hottest periods of the day. The central research question was therefore: to what extent do environmental heat stress and individual runner characteristics determine the time required to return to a safe level ($\text{PSI} < 3$) after running in Natitingou? The hypothesis was that a high ambient WBGT, a high end-exercise PSI and insufficient fluid intake would significantly prolong recovery. The objective was to quantify these effects and develop an operational predictive model of the required recovery time. To conceptualise the complex interactions between the microclimatic environment, exercise load and individual physiological response, a theoretical model was developed. Figure 1 summarises the functional relationships underpinning the experimental protocol, PSI calculation and recovery-time modelling.

Source: Adapted from Moran, Shitzer and Pandolf (1998) and Racinais et al. (2015).

Figure 1 shows that physiological strain does not arise from air temperature alone. Solar radiation, wind speed, relative humidity and running intensity act jointly on heat production and dissipation. Body temperature and heart rate are the two internal responses included in the PSI equation. Training status, acclimatisation and hydration profile modify this relationship without eliminating the influence of the ambient environment. Recovery kinetics then depend on moving the runner to a shaded area, available ventilation and immediate fluid intake. The model therefore distinguishes external heat stress, measured by WBGT, from internal physiological strain, assessed individually by PSI. This distinction is essential: two runners exposed to the same course may finish exercise with different PSI values, which explains why a uniform rest period does not provide equivalent protection for all participants.

2. Materials and methods

To assess physiological strain and model recovery time in amateur runners exposed to severe heat stress, a field experimental approach combined with multivariable statistical analysis was adopted. This section describes the geographical setting of the experiment, the study population, the measurement instruments used, and the procedures for calculating bioclimatic indices and modelling recovery time.

2.1. Study setting

The study was conducted in Natitingou, the administrative capital of Atacora Department in north-western Benin, between 9°58' and 10°34' N and 1°10' and 1°43' E. Covering an area of 3,045 km², the municipality comprises nine arrondissements, including five rural areas (Kotopounga, Kouaba, Kouandata, Perma and Tchoumi-Tchoumi) and four urban areas (Natitingou 1, 2 and 3, and Perpéyakou).

Figure 2 shows the geographical location of Natitingou Municipality, including its administrative boundaries, the road network used and the location of the experimental site.

The city is characterised by the Atacora mountain range, whose mountainous and undulating relief distinguishes the area from the southern plains. Located at an altitude of approximately 460 m and away from the direct maritime influence affecting the coast, the area belongs to the Sudanian climatic zone. It has a pronounced dry season and a single rainy season. Experimental trials were concentrated between February and April, when daytime temperatures and solar radiation reach their annual maxima. The selected running routes combined an open athletics track and a lightly shaded urban road circuit. Mineral surfaces favoured radiant heating, while ventilation varied with the orientation of the sectors crossed. Although amateur sport is mainly practised early in the morning or late in the afternoon, some training sessions and events occur during the middle of the day. The study specifically targeted the 12:00–15:00 period to document an adverse but representative extreme-exposure scenario. Recovery areas were established under a shaded, ventilated shelter equipped with seating, drinking water, portable fans and first-aid equipment.

2.2. Population and exercise protocol

The study included 84 amateur runners, 63 men and 21 women, aged 18–45 years, each of whom had been running at least once per week for at least six months. Exclusion criteria included unstable cardiovascular disease, fever or recent infection, use of medication affecting thermoregulation, and inability to sustain 45

minutes of exercise. A familiarisation session preceded the main trial. Maximal aerobic speed (MAS) was assessed using a progressive field test, after which the target running pace was set at approximately 70% of MAS. Each runner completed a single session between 12:00 and 15:00 comprising a 10-minute warm-up, 45 minutes of continuous running in the sun, and 30 minutes of seated recovery under shelter. Immediate termination of exercise was planned in the event of confusion, unsteady gait, chest pain, vomiting, or exceeding the thermal safety threshold defined by the protocol. Access to water remained unrestricted. For the recovery analysis, participants were grouped according to whether they consumed at least 500 mL of water during the first 10 minutes of recovery, classified as adequate rehydration, or spontaneously consumed less than 250 mL, classified as low fluid intake. The final sample was intended to reflect the diversity of amateur runner profiles in Natitingou.

Table 1 summarises the anthropometric, physiological and sporting characteristics of the participants included in the protocol.

Table 1
Morphological, physiological and sporting characteristics of runners included in the protocol.

Variable	Mean or count	Range or proportion
Men / women	63 / 21	75.0% / 25.0%
Age (years)	29.1 ± 5.8	18 to 45
Body mass index (kg/m ²)	22.9 ± 2.6	18.1 to 31.5
Maximal aerobic speed (km/h)	13.4 ± 1.8	9.5 to 17.8
Running experience (years)	3.2 ± 2.0	0.5 to 14.0
Weekly sessions	3.1 ± 1.2	1 to 6
Adequate immediate rehydration (≥ 500 mL)	54	64.3%
Low immediate fluid intake (< 250 mL)	30	35.7%

Source: Survey and field measurement data, February-April 2026.

The sample comprised a young, predominantly male group, with sufficient variability to examine the influence of age, body size and physical fitness. Mean MAS was consistent with regular amateur participation. The observed distribution between the two hydration behaviours, 64.3% versus 35.7%, allowed comparison of recovery kinetics. Water intake was not experimentally randomised but reflected runners’ spontaneous behaviour, justifying subsequent multivariable adjustment for potential confounders including WBGT, end-exercise PSI, MAS and age.

2.3. Data used

Synchronous monitoring of environmental variables and physiological responses required portable, validated measurement equipment. Table 2 presents the data collected, the instruments used, the sampling frequency and their role in the analysis.

Table 2
Data sources, characteristics, sampling frequency and analytical use.

Data	Source or instrument	Sampling frequency	Use
Air temperature (Ta) and relative humidity (RH)	Ventilated thermo-hygrometer in a portable shelter	1 minute	Microclimate characterisation
Black-globe temperature (Tg)	150-mm black globe	1 minute	Radiation and WBGT calculation
Wind speed (v)	Portable anemometer at 1.5 m height	1 minute	Ventilation along the course
Heart rate (HR)	Telemetric chest strap	5 seconds	Cardiovascular component of PSI
Body temperature (Tc)	Tympanic thermometer, same device and ear	Before exercise, end-exercise, then every 5 min	Thermal component of PSI
Perceived exertion (RPE)	0–10 numerical scale	End-exercise and recovery	Perception-strain mismatch
Hydration	Measured water volume (mL)	First 0–10 min of recovery	Predictor of recovery time

Source: *Experimental research protocol*, 2026.

The one-minute sampling interval for meteorological variables enabled precise calculation of WBGT for each session. Continuous heart-rate recording allowed cardiovascular drift to be monitored. Tympanic temperature provided a rapid, non-invasive field measure. Although more sensitive to ambient airflow than rectal temperature, its repeatability was optimised by using a single device, the same ear, and a standardised measurement protocol under shelter. Direct measurement of the volume of water consumed ensured rigorous participant classification without self-reporting bias.

2.4. Index calculation and statistical analysis

Outdoor Wet-Bulb Globe Temperature (WBGT) under solar radiation was calculated using the standard equation:

$$\text{WBGT} = 0.7 T_{\text{nwb}} + 0.2 T_{\text{g}} + 0.1 T_{\text{a}}$$

where T_{nwb} is the natural wet-bulb temperature, T_{g} is black-globe temperature and T_{a} is air temperature.

To assess atmospheric severity, calculated WBGT values were classified into four risk categories. The corresponding thresholds and activity recommendations are provided in Online Resource Table S1.

The Physiological Strain Index (PSI) was calculated at each time point using the equation proposed by Moran, Shitzer and Pandolf (1998):

$$\text{PSI} = 5 \times [T_{\text{c}}(t) - T_{\text{c}}(0)] / [39.5 - T_{\text{c}}(0)] + 5 \times [\text{HR}(t) - \text{HR}(0)] / [180 - \text{HR}(0)]$$

where $T_c(0)$ and $HR(0)$ are resting baseline values, and $T_c(t)$ and $HR(t)$ are the values measured at time t . PSI interpretation is provided in Online Resource Table S2.

A PSI score < 3 was selected as the criterion for return to low physiological strain. Recovery time was defined as the minimum time required for PSI to fall below 3 and remain below this value. Bioclimatic indices were calculated using BioKlima© v2.6. The statistical analysis plan is provided in Online Resource Table S3.

Analyses were conducted at a 5% significance level ($\alpha = 0.05$). The analytical plan progressed from description to prediction. Correlation analyses first assessed whether increases in WBGT, end-exercise heart rate or end-exercise temperature were accompanied by higher PSI values. One-way analysis of variance then tested for a graded relationship between heat categories and internal physiological strain. Student's t-test provided a simple comparison of recovery according to hydration behaviour, but was insufficient to establish an independent effect. Multiple regression therefore incorporated several factors simultaneously. Maximal aerobic speed represented physical fitness, age represented a general individual characteristic, and end-exercise PSI represented the physiological load actually accumulated. Error indices were used to assess the practical value of the model, because a strong statistical association alone would not have been sufficient if prediction errors exceeded the usual duration of a recovery break.

3. Results

Data collected from the 84 runners characterised ambient heat stress, tracked physiological changes during exercise and recovery, and supported development of a predictive model for the time required to return to a safe physiological state. Results are presented in three stages: assessment of microclimatic conditions, analysis of cardiovascular and thermal recovery kinetics, and modelling of recovery time according to fluid intake and training status.

3.1. Microclimatic conditions and level of physiological strain

The 84 experimental sessions were conducted under a mean WBGT of $29.8 \pm 1.6^\circ\text{C}$. Mean air temperature was $35.7 \pm 2.0^\circ\text{C}$, relative humidity was $29.9 \pm 3.2\%$, and black-globe temperature was $44.0 \pm 3.1^\circ\text{C}$. Physiologically, mean heart rate increased from 70.4 ± 7.9 bpm at rest to 161.7 ± 13.9 bpm at the end of the run. Tympanic temperature rose from 36.73 ± 0.19 to $38.34 \pm 0.32^\circ\text{C}$. Mean end-exercise PSI was 7.1 ± 1.0 . The high-strain threshold, $\text{PSI} \geq 7$, was reached or exceeded by 54.8% of runners, while 2.4% crossed the very-high-strain threshold, $\text{PSI} \geq 9$. The dynamics of internal heat accumulation and dissipation were monitored throughout the session.

Figure 3 shows the mean PSI trajectory recorded during the 45 minutes of exercise in the sun and the subsequent 30 minutes of shaded recovery.

Source: Statistical analysis of experimental field data, 2026.

The curve shows a continuous increase in PSI during running, with a marked acceleration after the thirtieth minute as the rise in body temperature adds to an already elevated heart rate. At exercise cessation, the mean crosses the high-strain threshold ($\text{PSI} \geq 7$). PSI begins to decline as soon as participants move under

the shaded shelter, but the reduction is gradual. After 10 minutes of recovery, a substantial proportion of runners remain in the moderate-to-high strain range. On average, the safety threshold (PSI < 3) is not approached until approximately the twentieth minute, with pronounced inter-individual variability.

This variability confirms that a fixed 10-minute break is insufficient to ensure recovery across the whole group and supports modelling an individualised recovery period. To examine the direct impact of atmospheric conditions on internal strain, responses were stratified according to the four WBGT exposure categories. Table 3 details physiological strain and recovery times for each thermal category.

Table 3
Physiological strain (PSI) and recovery time according to WBGT category.

WBGT (°C)	n	Mean WBGT (°C)	End-exercise PSI	PSI ≥ 7 (%)	PSI ≥ 9 (%)	Time to PSI < 3 (min)
< 28.0	14	27.3	5.9 ± 0.6	7.1%	0.0%	16.4
28.0-29.9	30	29.1	6.9 ± 0.8	43.3%	0.0%	20.1
30.0-31.9	30	30.8	7.4 ± 0.7	73.3%	0.0%	23.7
≥ 32.0	10	32.5	8.3 ± 0.8	100.0%	20.0%	27.9

Source: Field measurements and calculations using BioKlima v2.6, 2026.

The data reveal a clear gradient between microclimatic severity and the physiological response. When WBGT remained below 28°C, mean PSI was 5.9 and only 7.1% of runners reached the threshold of 7. This proportion increased to 43.3% between 28.0 and 29.9°C, then to 73.3% between 30.0 and 31.9°C, reaching 100% at or above 32°C. In parallel, mean time required to return to PSI < 3 increased from 16.4 to 27.9 minutes. ANOVA confirmed a highly significant difference between categories ($p < 0.001$). A strong positive correlation was observed between WBGT and end-exercise PSI ($r = 0.71$). To explore relationships between climatic variables, physiological parameters and recovery time, a bivariate analysis was conducted. The full Pearson correlation matrix is provided in Online Resource Table S4.

End-exercise PSI showed its strongest correlations with end-exercise heart rate ($r = 0.87$) and end-exercise body temperature ($r = 0.79$), as expected from the equation used to calculate the index. WBGT remained strongly correlated with recovery time ($r = 0.68$), supporting its relevance as an indicator of external exposure. The accumulated internal strain, represented by end-exercise PSI, was also positively associated with recovery time ($r = 0.59$). Runners who accumulated greater internal strain therefore required longer recovery.

3.2. Cardiovascular and thermal kinetics during recovery

During shaded recovery, restoration of central physiological functions did not occur at the same rate across physiological systems. Figure 4 highlights the temporal lag between the rapid decline in heart rate and the slower reduction in tympanic temperature.

Source: Physiological data from the field experiment, 2026.

Figure 4 demonstrates two distinct rates of recovery. Heart rate falls rapidly during the first five minutes after muscular work ceases. In contrast, tympanic temperature declines slowly because of thermal inertia and the continued transfer of stored heat from the working muscles towards the body core and skin. After 10 minutes of recovery, heart rate suggests an apparent return towards resting conditions, whereas internal temperature remains elevated. This lag shows that pulse observation alone is insufficient to confirm thermal recovery and supports continued use of PSI. The quantified changes during 30 minutes of sheltered follow-up are summarised in Online Resource Table S5.

Group means measured at fixed five-minute intervals are provided in Online Resource Table S5. Mean PSI falls below 3 at 25 minutes, which is consistent with the overall mean calculated from individual recovery times, ranging from 20.2 to 24.5 minutes according to hydration level.

Within 10 minutes of recovery, mean heart rate decreases by 57.1 bpm, whereas body temperature falls by only 0.27°C. Perceived exertion declines to 3.5/10 while mean PSI remains at 4.9, corresponding to moderate strain. At group level, PSI < 3 is reached at 25 minutes (2.9 ± 0.8). Thus, the fall in perceived fatigue clearly precedes thermophysiological normalisation.

3.3. Effect of hydration and training status

Fluid intake initiated immediately after running had a direct modifying effect on the decline in physiological strain. Figure 5 compares PSI recovery curves between runners with adequate rehydration (≥ 500 mL) and those with low fluid intake (< 250 mL).

Source: Recovery measurements according to hydration profile, 2026.

The trajectories progressively diverge from the fifth minute of recovery. Mean time to reach PSI < 3 was 20.2 ± 4.8 minutes among adequately rehydrated runners, compared with 24.5 ± 4.7 minutes among those with low fluid intake. This unadjusted difference of 4.3 minutes in favour of greater fluid intake was highly significant ($p < 0.001$). Immediate water intake favoured restoration of plasma volume and limited persistence of an elevated heart rate during recovery. Participants with MAS ≥ 14 km/h also recovered more rapidly than those with lower MAS, with an unadjusted mean advantage of approximately four minutes. In contrast, age showed no significant univariable effect in this population of young adults aged 18–45 years.

3.4. Modelling recovery time

To isolate the independent effect of each factor, multiple linear regression was used to predict the time required to return to PSI < 3. The final model was highly explanatory ($R^2 = 0.668$; adjusted $R^2 = 0.647$; $p < 0.001$). Root mean square error was 3.0 minutes (RMSE), and mean absolute error was 2.4 minutes (MAE). The resulting predictive equation was:

$$RT = -31.59 + 1.55 \text{ WBGT} + 1.42 \text{ PSI}_{\text{end}} - 0.47 \text{ MAS} + 0.06 \text{ Age} + 4.46 \text{ LFI}$$

where RT is recovery time in minutes, WBGT is expressed in °C, PSI_{end} is end-exercise PSI, MAS is expressed in km/h, Age in years, and LFI is coded 1 for low fluid intake (< 250 mL) and 0 for adequate immediate rehydration (≥ 500 mL).

Table 4 presents the regression coefficients, standard errors and levels of statistical significance.

Table 4
Coefficients of the multiple linear regression model for recovery time, in minutes.

Variable	Coefficient β	Standard error	95% CI	p value
Constant	-31.59	7.61	-46.74 to -16.43	< 0.001
WBGT, per 1°C	1.55	0.32	0.92 to 2.18	< 0.001
End-exercise PSI, per 1 point	1.42	0.52	0.37 to 2.46	0.009
MAS, per 1 km/h	-0.47	0.20	-0.88 to -0.07	0.022
Age, per 1 year	0.06	0.06	-0.06 to 0.18	0.305
Low fluid intake (0/1)	4.46	0.72	3.03 to 5.89	< 0.001

Source: *Multiple linear regression modelling of field data, 2026.*

With individual and physiological characteristics held constant, each 1°C increase in WBGT increased the required recovery time by 1.55 minutes. Each additional point of end-exercise PSI added 1.42 minutes. Better physical fitness, represented by MAS, shortened recovery by 0.47 minutes for each additional km/h. Finally, inadequate immediate rehydration produced the largest adjusted penalty, prolonging recovery by 4.46 minutes. To assess the operational accuracy of the equation, predicted recovery times were compared with values observed in the field. Figure 6 illustrates this agreement.

Source: *Evaluation of the predictive model using field data, 2026.*

The points align satisfactorily along the line of perfect equality ($y = x$). The modest discrepancies observed for very long recovery times (≥ 30 min) may be explained by inter-individual factors not included in the model, such as individual sweat rate or sodium status. With a mean absolute error of 2.4 minutes, the model provides sufficient precision to support field recommendations in five-minute increments.

The scatter of points around the line of equality indicated acceptable agreement for an initial field estimate. The largest deviations concerned the longest recovery times, probably because unmeasured factors such as sweat rate, sleep, recent acclimatisation or sodium intake influenced recovery.

3.5. Mismatch between perceived fatigue and actual physiological strain

Analysis of subjective perceived exertion identified an important safety concern. Online Resource Figure S1 compares the temporal evolution of perceived exertion (RPE, 0–10) with PSI during recovery.

Online Resource Figure S1 identifies a risk-underestimation window from approximately 5 to 15 min of recovery: perceived fatigue falls rapidly while physiological strain remains elevated. This mismatch may encourage premature return to exercise if recovery decisions rely on symptoms alone.

4. Discussion

The findings show that 45 minutes of running during the hottest hours of the day in Natitingou, under a WBGT of approximately 30°C, induces substantial physiological strain in amateur runners, with a mean PSI of 7.1 and more than half of participants exceeding the high-strain threshold of $\text{PSI} \geq 7$. This finding supports the applicability of the Physiological Strain Index developed by Moran, Shitzer and Pandolf (1998) in exercise-heat settings and reinforces the need for individualised monitoring, as recommended by Buller et al. (2023). The dominant influence of ambient heat stress, represented by WBGT, on prolonged recovery is consistent with ISO 7243 (2017) and the recent work of Yang et al. (2026).

With regard to hydration, the longer recovery required when fluid intake was insufficient, an adjusted increase of 4.46 minutes, is consistent with observations by Moran, Montain and Pandolf (1998) and Montain and Coyle (1992). Hypohydration exacerbates exercise hyperthermia and cardiovascular drift by reducing stroke volume, thereby slowing the decline in heart rate during recovery. The temporal dissociation shown in Fig. 4 between the rapid fall in heart rate and the persistence of elevated body temperature is a central physiological finding. When exercise ceases, the immediate reduction in muscular metabolic demand produces rapid cardiovascular relief.

In contrast, heat accumulated within tissues during 45 minutes of continuous running takes considerably longer to dissipate. This residual thermal inertia has been documented in calorimetric studies by Kenny et al. (2008). This lag explains the risk-underestimation window shown in Online Resource Figure S1: the runner feels recovered because breathlessness has subsided and pulse rate has fallen, although body temperature remains elevated. Relying solely on subjective sensations or pulse measurement therefore creates a substantial risk of resuming exercise too early.

Methodologically, tympanic thermometry facilitated repeated field monitoring. However, as noted by Ganio et al. (2009) and Morán-Navarro et al. (2019), this technique is more sensitive to wind and skin sweat than rectal measurements or ingestible temperature sensors. Absolute temperature values should therefore be interpreted cautiously. In addition, intensive active-cooling strategies, such as cold-water immersion or cooling vests, examined by Stephens et al. (2018) and Seeley and Sherman (2021), were not evaluated here; the protocol relied on passive shaded recovery with ventilation and hydration. Finally, the sample size ($n = 84$), the predominance of male participants and the cross-sectional nature of the experiment indicate the need for further prospective validation including larger female samples, adolescents and less-trained participants.

4.1. Practical implications and operational recommendations

Given the risk of heat exhaustion identified during running in the hottest hours, translating the empirical findings into practical guidance is essential for participant safety. This section proposes simple decision-support tools, including recovery tables and organisational recommendations, for coaches, clubs and organisers of sporting events in dry tropical/Sudanian environments. The predictive equations were converted into simplified operational rules. Proposed recovery periods were rounded upwards as a precaution and assume recovery under a ventilated shelter with cool water available. Table 5 presents this operational guide.

Table 5

Proposed minimum exercise-recovery ratios according to PSI and WBGT levels in Natitingou.

Situation / strain level	Ratio or decision	Minimum operational action
PSI < 5 and WBGT < 28.0°C	45 min exercise / 10 min recovery	Recover in shade, unrestricted hydration, check pulse before resuming
PSI 5-6.9 or WBGT 28.0-29.9°C	40 min exercise / 15 min recovery	Reduce pace, break exercise into shorter bouts, mandatory reassessment at 15 min
PSI 7-8.9 or WBGT 30.0-31.9°C	30 min exercise / 20–25 min recovery	Recover under a ventilated shelter, measured hydration (≥ 500 mL), check T _c and neurological status
PSI ≥ 9 or WBGT $\geq 32.0^\circ\text{C}$	Stop the session	Immediate active cooling, close monitoring, no return to exercise the same day
Confusion, collapse, vomiting or chest pain	Absolute medical emergency	Cool immediately using spraying/ice and arrange urgent medical evacuation

Source: *Operational synthesis, 2026.*

The guide prioritises caution and simplicity. At WBGT < 28°C and low PSI, a 10-minute break may be sufficient before reassessment. Once PSI reaches 7 or WBGT exceeds 30°C, the proposed exercise duration is shortened and recovery extended to at least 20 minutes. The highest category does not include a return-to-exercise ratio, because PSI ≥ 9 or WBGT $\geq 32^\circ\text{C}$ indicates a situation requiring cessation, cooling and an individualised decision. The final row takes precedence over all others. Neurological signs, collapse or chest pain require urgent management even if the monitoring device displays a less concerning value. This decision table requires validation against real-world data before institutional use.

Online Resource Table S6 allocates responsibilities before exercise, during running, throughout recovery, and after an incident. It emphasises environmental assessment, preparation of a shaded recovery area, recognition of warning signs, repeated recovery checks, and incident documentation.

5. Conclusions

This study shows that endurance running during the hottest hours of the day in Natitingou generates very high thermophysiological strain in amateur athletes. The mean PSI measured at the end of exercise, 7.1 ± 1.0 , indicates a substantial risk of heat exhaustion.

The study makes three principal contributions:

- Heart rate and perceived fatigue decline considerably faster than tympanic body temperature, creating a risk-underestimation window between the fifth and fifteenth minutes of recovery that may encourage premature resumption of exercise.
- Consuming an adequate volume of water (≥ 500 mL) immediately after running accelerates the decline in PSI and reduces the time required to return to the safety threshold (PSI < 3) by 4.46 minutes after multivariable adjustment.

- The regression equation explains 66.8% of the variability in recovery time using WBGT, end-exercise PSI, MAS and hydration, with a mean prediction error of 2.4 minutes.

In practical terms, these findings support avoiding running sessions between 12:00 and 15:00 during the dry season in Sudanian climates. When exposure is unavoidable under $WBGT \geq 30^{\circ}C$, strict protocols should include at least 20 minutes of passive shaded recovery and measured rehydration. Further prospective studies using a reference core-temperature measure, such as an ingestible sensor or rectal thermometry, together with individual sweat-rate measurements, would refine the recovery guide for the range of sports practised in dry tropical environments.

Declarations

Competing interests

The author declares no competing interests.

Ethics approval

The study protocol received prior ethical approval from the Research Ethics Committee of LACEEDE, University of Abomey-Calavi, Benin (approval no. CE-LACEEDE-2025-34; 29 December 2025). The study was conducted in accordance with the applicable institutional ethical standards and the principles of the Declaration of Helsinki.

Consent to participate

Informed consent was obtained from all individual participants included in the study.

Consent to publish

Not applicable. The manuscript contains no identifiable individual participant information.

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Author Contribution

N.P.M.BOKO conceived and designed the study, performed data collection, conducted the statistical analyses and modeling, prepared the figures and tables, and wrote and revised the complete manuscript.

Data Availability

The datasets generated and analyzed during the current study are available from the corresponding author on reasonable request.

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Figures

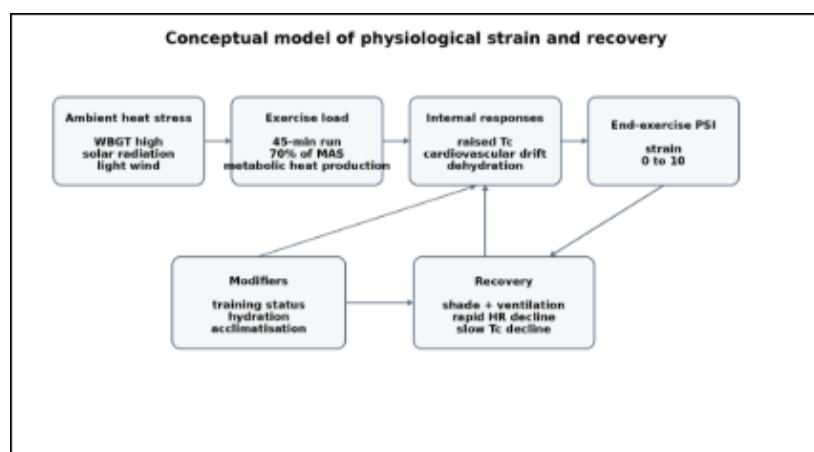


Figure 1

Conceptual model linking heat stress, exercise load, PSI and recovery.

Source: Adapted from Moran, Shitzer and Pandolf (1998) and Racinais et al. (2015).



Figure 2

Schematic location of Natitingou and the experimental site.

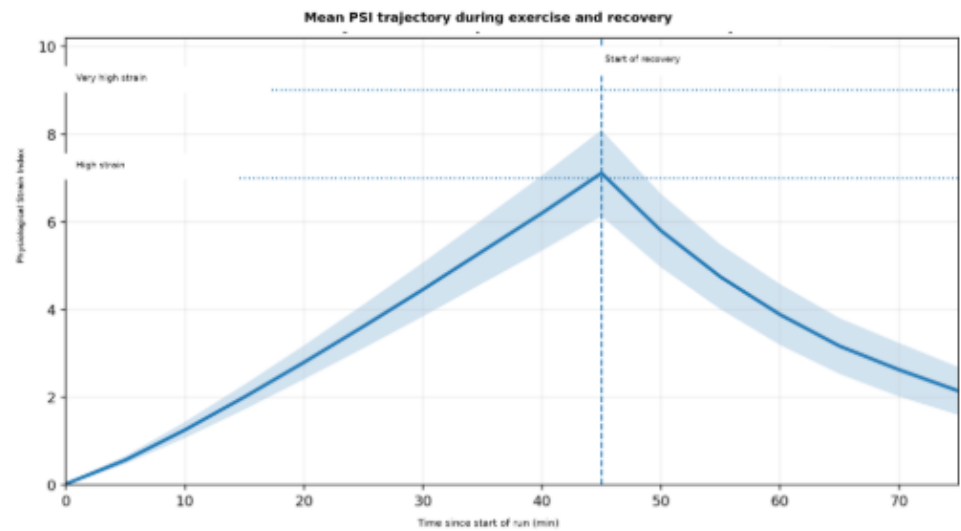


Figure 3

Mean temporal evolution of the Physiological Strain Index (PSI) during exercise and recovery.

Source: Statistical analysis of experimental field data, 2026.

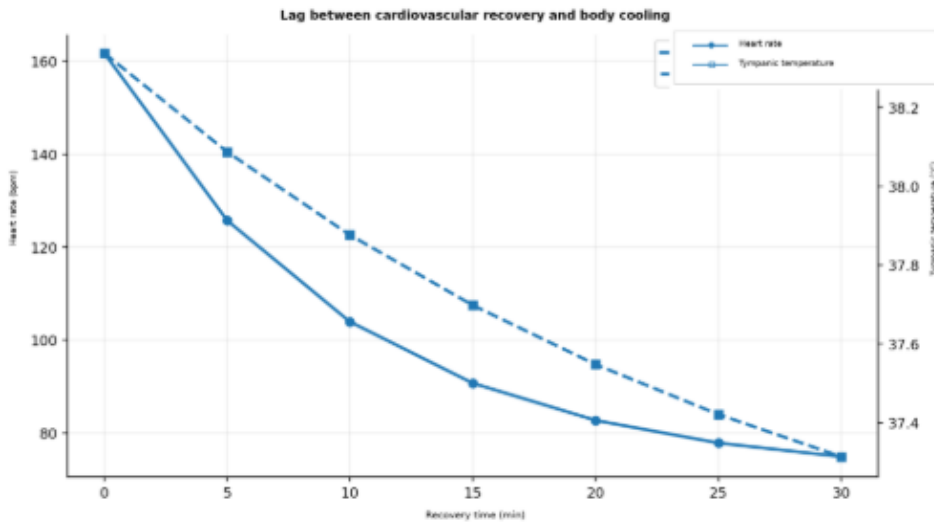


Figure 4

Comparative kinetics of heart-rate decline and tympanic-temperature reduction during recovery.

Source: *Physiological data from the field experiment, 2026.*

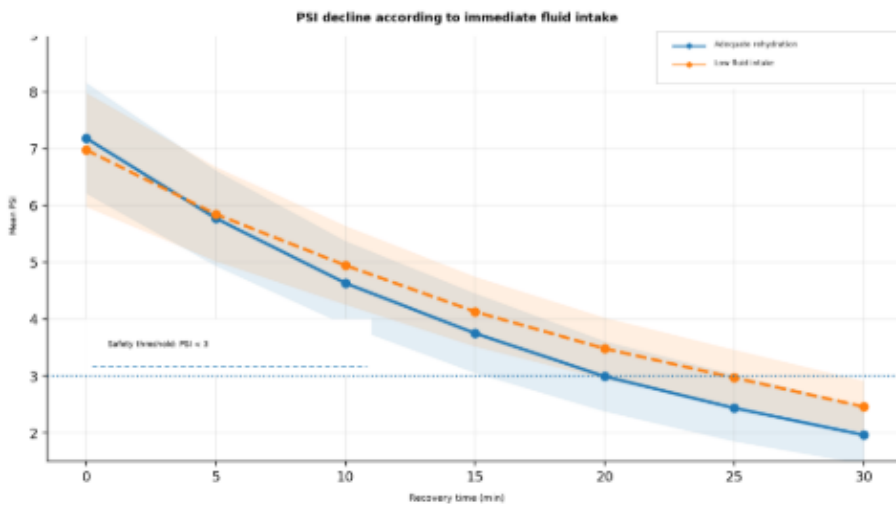


Figure 5

Decline in PSI during recovery according to immediate fluid intake.

Source: *Recovery measurements according to hydration profile, 2026.*

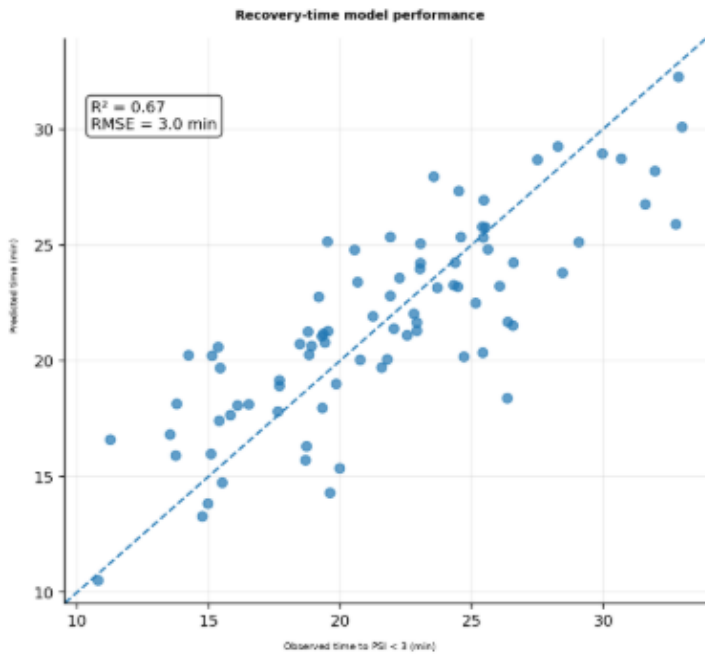


Figure 6

Agreement between observed recovery times and times predicted by the model.

Source: Evaluation of the predictive model using field data, 2026.

Supplementary Files

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