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HEAT FLUX MONITORING USING SATELLITE BASED IMAGERY AT KARAPITI ('CRATERS OF THE MOON') FUMAROLE AREA, TAUPO, NEW ZEALAND

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ABSTRACT

LANDSAT thermal infrared data (30 m pixel resolution), supported by spot ground measurements, were used in this study to investigate changes between 1990 and 2011 in the radiative heat flux (RHF) from the 0.5 km^2 Karapiti fumarole area, at Wairakei Geothermal Field, Taupo, New Zealand. An objective was to calculate the net RHF of the geothermal area in order to reduce the effect of solar heating in these satellite infrared images. The result showed that the RHF decreased between1990 and 2011 by a total of about 29 MW. The net RHF (geothermal radiative heat flux) decreased by about 13 MW from 2000 to 2011. Another method of estimating net RHF, by subtracting the total incident direct solar heat load, also showed a decreasing trend, from about 96 to 67 MW during the study period. A vegetation index from the LANDSAT-TM/ETM+ VNIR bands (NDVI) was used to undertake a land-cover study. Results implied that the area of healthy vegetation at Karapiti progressively increased during this period. This supports the evidence for a decrease in geothermal heat losses, because the health of thermally-stressed vegetation is inversely related to shallow ground temperature. Images of apparent land-surface temperature (LST) were statistically sampled using a random spatial distribution of 100 points. Though the results show large variations with time, overall, there is a decreasing trend. As expected, there is a strong correlation between LST and RHF from all analyzed images. Spot ground estimations of heat flux using a calorimeter, when repeated, also showed, on average, a decreasing trend of heat flux between 2000 to 2009, although several sites showed stable heat flux. Further supporting evidence came from repeated ground-based temperature-depth profiles, which showed that the near-surface boiling point depth lowered in level at most sites between 2000 and 2011, although several sites located in actively-steaming bare-ground (~98°C at ~0.1m depth) remained relatively stable. In conclusion, satellite imagery and supporting ground-based evidence suggest a pattern of gradual decline (despite some time and spatial variation) in overall heat flux over the past decade from the Karapiti fumarole area.

Keywords: Radiative heat flux, geothermal heat flux, Landsat TIR data, Karapiti Fumaroles, New Zealand.

INTRODUCTION

The Karapiti fumarole area ('the Craters of the Moon') is situated within the Wairakei – Tauhara geothermal system in the central part of the North Island of New Zealand. The total area of steaming ground, craters and fumaroles is about 0.54 km^2, of which about 0.35 km^2 is intensely active (Fig.1). It is a well-studied liquid-dominated geothermal reservoir system in the Taupo Volcanic Zone (TVZ), New Zealand (Bromley and Hochstein, 2005). The first heat flow measurements in the Karapiti area were reported 50 years ago (Ledger, 1950). The second set of heat flow measurements were taken after large changes of heat output in this fumarole field area during the early 1960's (Dawson, 1964). Allis (1979) calculated a total heat loss of 220 MW in 1978, with estimated error bounds of +/- 20%. Mongillo and Allis (1988) checked it by qualitative reassessment, and found it to be unchanged 10 years later. During a

1999 re-survey of several fumaroles in the Karapiti area, it was shown that fumarole measurements can provide reproducible heat output data if the disturbing role of air inflow at the vent can be eliminated or reduced (Hochstein and Bromley, 1999). Bromley and Graham (1999) reassessed total Karapiti heat loss from 1997 thermal airborne IR imagery, using four grades of thermal ground, to be 200 +/- 40 MW, of which ~50% was from steaming ground (convective heat loss). In 2004, Bromley and Hochstein (2005) assessed total heat flux to be about 245 +/- 40 MW, including discharges from fumaroles and steam vents within the 0.35 km^2 active area at Karapiti. They also estimated total heat flux using aerial infrared data to assess the areas of various grades of thermal ground and the numbers of active steam vents.

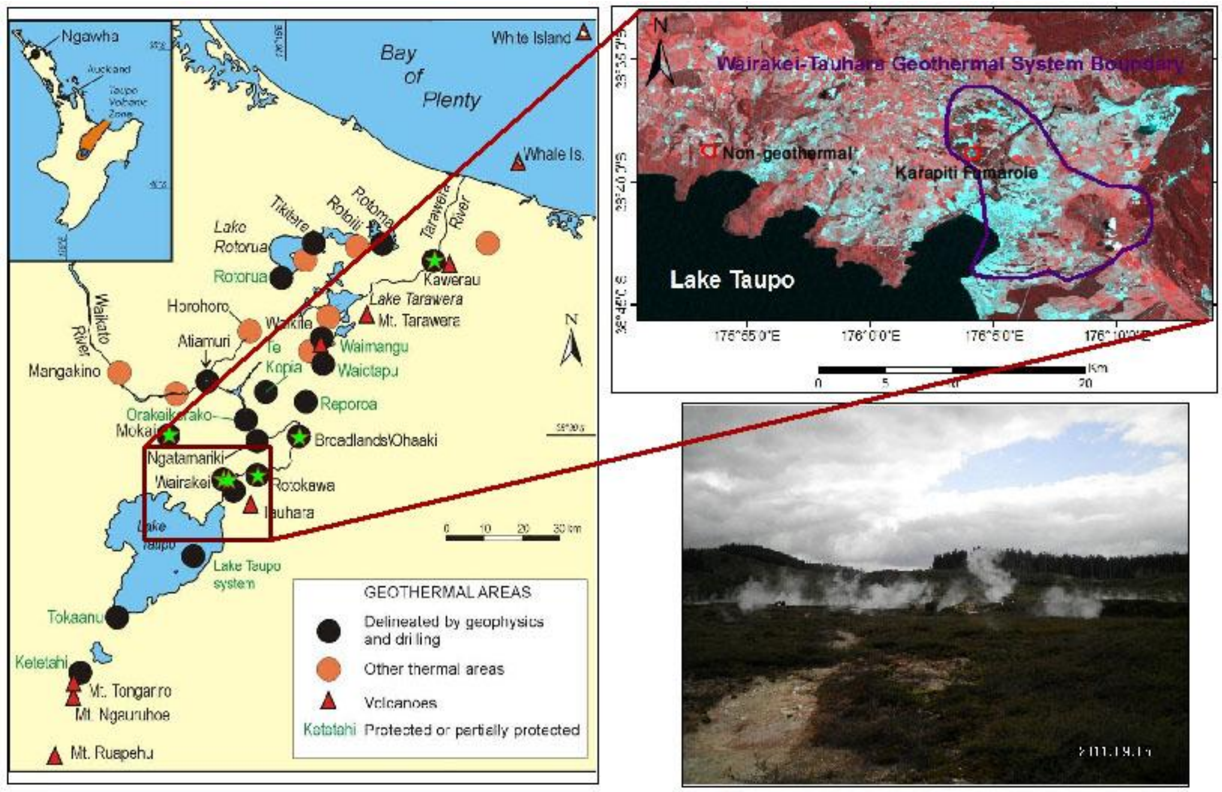

Figure 1: Study area.

Hunt et al (2009) summarized the changes in total heat loss from 1950 until 2005, showing an increasing trend from about 40 MW in 1950 to 400 MW by 1964, then a decrease to 220 MW by 2005. The latest reservoir simulation model of surface heat-flux at Karapiti also shows a heat pulse in the 1960's, caused by liquid pressure decline, boiling, and shallow steam-zone creation, and followed by a steady decline after 1970 because of declining steam-zone pressures (O'Sullivan et al., 2009).

The prime objective of our study was to monitor total radiative heat flux using Landsat infrared data, supported by repeat spot ground measurements, from 1990 to 2011, in the Karapiti fumarole area. An objective was to calculate the net RHF (geothermal radiative heat flux) of the geothermal area after subtracting a mean RHF from a nearby, non-thermally active (or background) region of grassland, located at the same latitude, in order to reduce the effect of solar heating in these satellite infrared images (all of which were recorded in mid-summer at about 9:50 am). We estimated net geothermal radiative heat losses in another way by subtracting the total incident direct solar heat load from the total RHF of the analyzed images.

MATERIALS USED FOR THIS STUDY

Landsat TM and Enhanced Thematic Mapper plus (ETM+) images were used for this study (path/row: 72/87). A total of 7 sets of images were obtained from the USGS Earth Resource Observation Systems Data Center. One set of images from Landsat TM was acquired on 25 December 1990, and has 7 multispectal bands, including a TIR band. Originally 120 m in resolution, it has subsequently been resampled to 30 meter resolution. Others images were ETM+ with 8 multispectal bands, including: 4 VNIR, 2 SWIR (Shortwave infrared), 1 PAN (Panchromatic) and 1 TIR. The ETM+ imageries were also acquired during New Zealand's mid-summer on 4/2/2000, 5/1/2001, 26/12/2002, 19/1/2006, 9/1/2008 and 1/1/2011 respectively. The ETM images have two channels of thermal infrared data (high and low gain) at 30 meter resampled resolution. We used the high gain option for more detail analysis. Local meteorological air temperature data was obtained from the NIWA (National institute of Water and Atmospheric Research) website using the nearest station, Taupo AWS (Airways station). For estimating the atmospheric transmissivity at the time of image acquisition, we used the NASA (National Aeronautics and Space Administration) atmospheric correction parameter calculator, by entering the location and time, and using the mid-latitude, summer, standard, upper-atmosphere profile.

METHODOLOGY

Satellite Image Pre-processing

The Landsat images were acquired at times when the atmospheric conditions were very clear. The USGS Earth Resource Observation Systems Data Center was corrected the radiometric and geometrical distortions of the images to a quality level of '1G' before delivery. The Landsat image was further rectified to a common (WGS84) geographic (Lat/Lon) coordinate system, mapped at 1:24,000 scales, and was resampled using the nearest neighbor algorithm with a pixel size of 30 by 30 m for all bands including the thermal band. The resultant RMSE (root mean square error) was found to be less than 0.5 pixels. The 'dark object subtraction' method has been applied for atmospheric correction of all images, using an appropriate transmissivity value. After extracting an image subset for the desired study area, we used the 'ERDAS Imagine' model of Landsat 7 reflectance to obtain reflectance values for all VNIR and SWIR bands of all images.

Measurement of RHF from Satellite Images

The following steps were taken for estimating radiative heat flux for the study area:

Normalized Differential vegetation Index (NDVI)

NDVI is an index of vegetation abundance, used as the indication factor of vegetation growth state, which is related to biomass, chlorophyll content and water stress. Generally, vegetated areas have high reflectance in the near infrared and low reflectance in the red visible region. NDVI defined as: NDVI= $(\rho_2-\rho_1)/(\rho_2+\rho_1)$, where ρ_2 represents the reflectance measured in the near infrared, and ρ_1 represents the reflectance corresponding to the red wavebands (Rouse et al., 1974). The NDVI value ranges from -1 to +1. In this index green vegetation has high values, water has negative values and bare soil has a value around 0.

Spectral emissivity

The NDVI based spectral emissivity method was applied for estimating the emissivity of this region (Valor and Caselles, 1996), for all images in this study.

Land surface temperature

The Land Surface Temperature (LST) was computed from the TIR band of corrected Landsat TM and ETM+ images. The satellite passed over the studied area in the morning (approximately 09:50 am), so the solar heating effects are not at their maximum value. The thermal IR (high gain for ETM+) images in this study were transformed into kinetic land surface temperature (LST) pixel by pixel, by using the mono-window algorithm in this study LST (Qin et al., 2001; Mia et al., 2011).

Radiative heat flux

Theoretical radiative heat flux has been calculated using the following equation (Bromley et al., 2011),

$$Q_r=\tau\sigma\varepsilon A\,(T_s^4 - T_a^4) \quad \ldots\ldots (7)$$

Where,

Q_r= radiative heat flux (W/m^2), τ = atmospheric transmissivity, σ =stefan-boltzmann constant, ε = emissivity, A = Area (m^2), T_s = Land surface temperature (k), T_a = ambient temperature (k).

Geothermal radiative heat flux (GHF_R)

We estimated net geothermal radiative heat losses using two methods. Firstly, we subtracted the mean value of the radiative heat flux from a similarly sized area near Kinloch about 20 km west of the Wairakei geothermal system boundary, on the same latitude as the Karapiti fumarole area (for equivalent solar radiation). Secondly, we calculated the Potential Annual Direct Incident Solar Radiation (PAIDSR) from a 90 m SRTM digital elevation model (DEM) of the Karapiti study area (McCune and Keon, 2002) to take solar effects into account.

Analysis of heat flux from spot measurement data

We analyzed the spatial distribution of total heat flux data from seven ground stations, measured using a calorimeter, as described by Bromley and Hochstein (2005) and Hochstein and Bromley (2007), along with additional unpublished results collected by the same authors after 2007. The results demonstrated a declining trend in total heat flux at most sites between 2002 and 2009 (Fig. 7). The few exceptions were at sites located in relatively-hot steaming-ground locations. Data from repeat ground-based temperature-depth profiles were also analyzed. The analysis showed that the near-surface boiling point depth has reduced in level (signifying near-surface cooling) at most sites between 2000 and 2011 (Fig. 8). A few exceptions were again located in areas of relatively hot steaming ground where the boiling temperature (~98°C) was at about 0.1 m depth.

RESULTS AND DISCUSSIONS

The NDVI value has been divided into three parts to identify three land-cover types in our study area. The NDVI values below 0.2 correspond to bare soil, from 0.2 to 0.5 correspond to mixed land (some bare ground, some sparse vegetation) and above 0.5 correspond to stressed vegetation. The 'baresoil'(<0.2 NDVI, as defined) was about 2.7% of the total study area in 1990, decreased to about 1% in 2002, and then 0% in 2006, 2008, and 2011. The mixed land was about 42% in 1990, but had also decreased to about 22% by 2011 (Fig.2). The area of stressed vegetation increased from 56% in 1990 to 78% in 2011. The calculated emissivity value (based on NDVI) ranged from about 0.96 to 0.99 throughout the study period. The higher emissivity values indicate more vegetation; the lower values relate to bare or mixed land. The land surface temperature (LST) of Karapiti shows some large variations in both maximum and minimum value between 1990 and 2011. The highest LST for an individual pixel was about 51.4°C in 2011 and the lowest was about 15.4°C in 2002 (Fig.3). We calculated the average LST above ambient using randomly sampled points (approx. 100) within the Karapiti area (Fig.4). Though the overall trend was a decline, there were also variations with time. The span in pixel values of radiative heat flux for each date is illustrated in Fig.5. Overall, the total radiative heat flux (RHF) of Karapiti reduced by about 29 MW from 1990 to 2011, although some variations with time are apparent. The highest radiative heat flux was about 262.73 MW in 2001 and the lowest was 227.52 MW in 2011. We estimated the radiative heat flux of a background non-geothermal area near Kinloch, 10 km west of Karapiti, but on the same latitude and image path. Geothermal radiative heat flux was calculated by subtracting the mean value of the non-geothermal region from all RHF analyzed images (Fig.6). Overall, GHF has been decreasing over this period in Karapiti. We also calculated GHF of Karapiti after subtracting the total potential solar incident heat load from total radiative heat flux for each image. The total average solar heat load was calculated to be about 160.4 MW. So, the highest net GHF was about 102 MW in 2001 and lowest was about 67 MW in 2011. The results also showed a generally decreasing trend from 1990 to 2011. Based on satellite image analysis, as well as ground estimation, the total heat flux at Karapiti is in gradual decline (despite some spatial and temporal variations). The satellite infrared information is a good option for monitoring heat losses relatively efficiently.

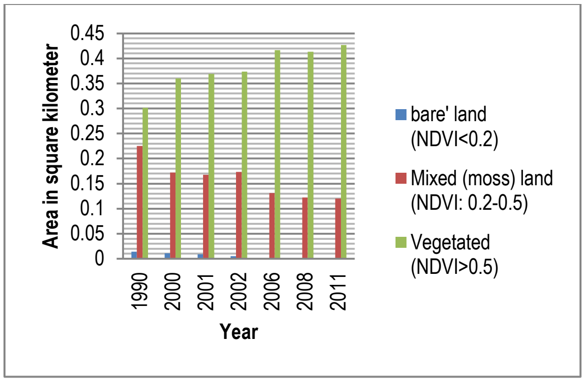

Fig.2: Apparent landcover changes with time based on NDVI index.

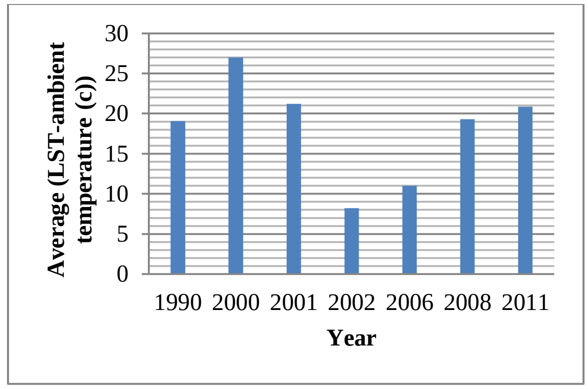

Figure 4: Trends with time in randomly sampled average Land Surface Temperature (LST) above ambient.

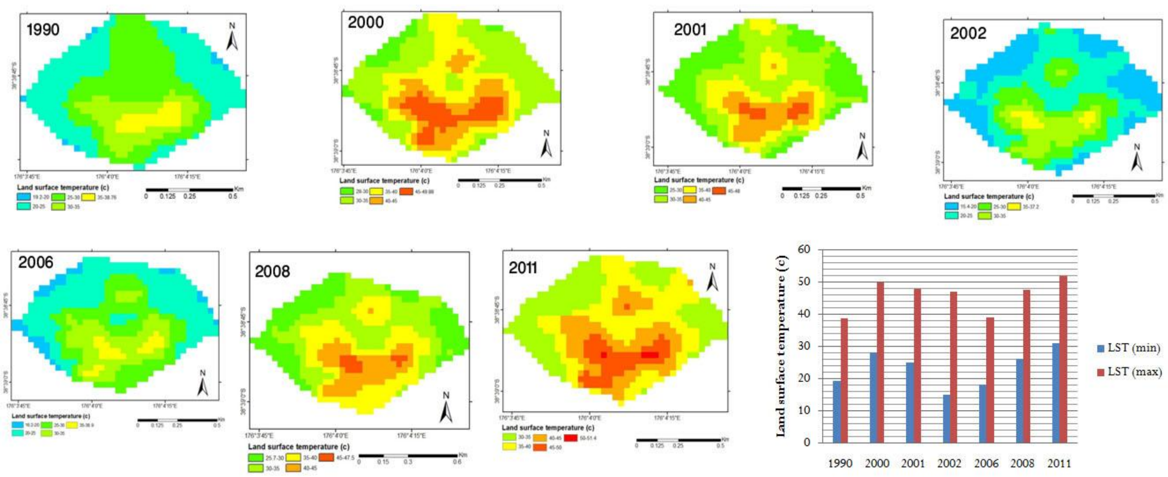

Figure 3: Satellite infrared estimated LST on Karapiti

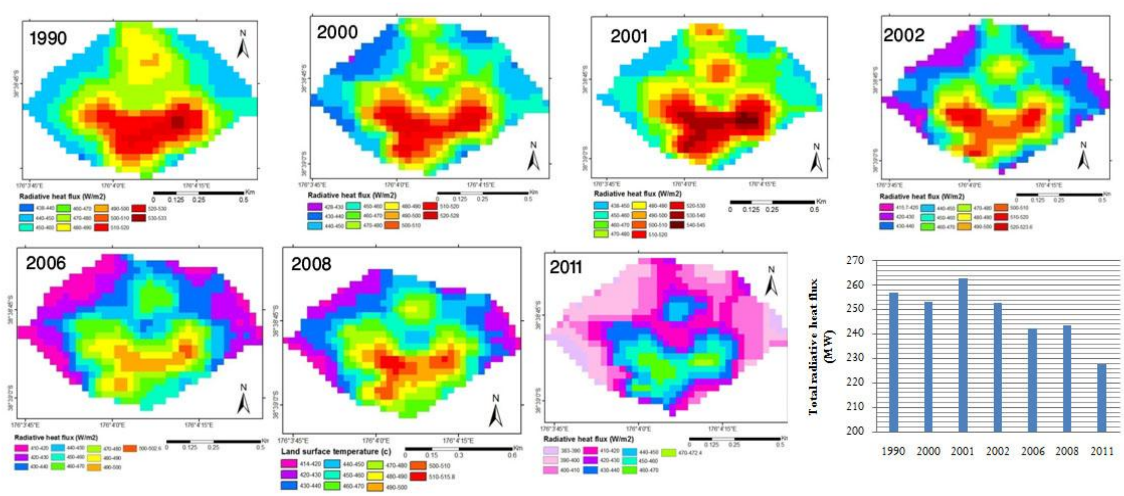

Figure 5: Radiative heat flux including solar in karapiti.

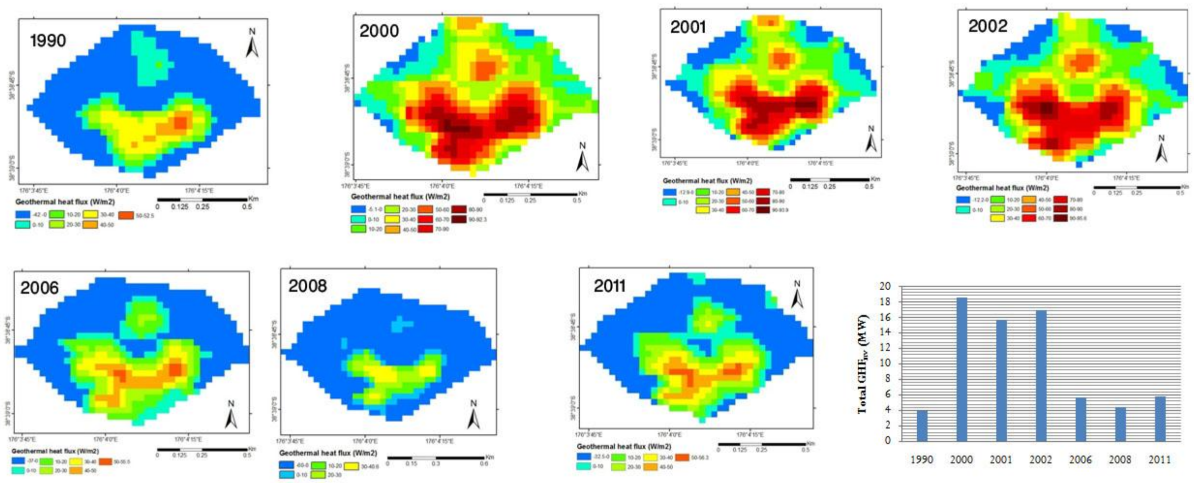

Figure 6: Geothermal radiative heat flux after reducing for solar radiation using background region.

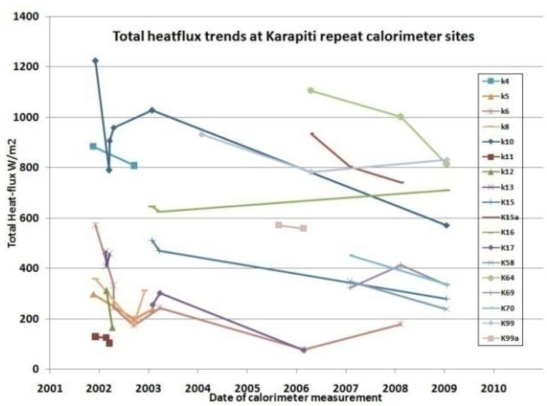

Figure 7: Ground based measured total heat flux trends at Karapiti repeat calorimeter sites.

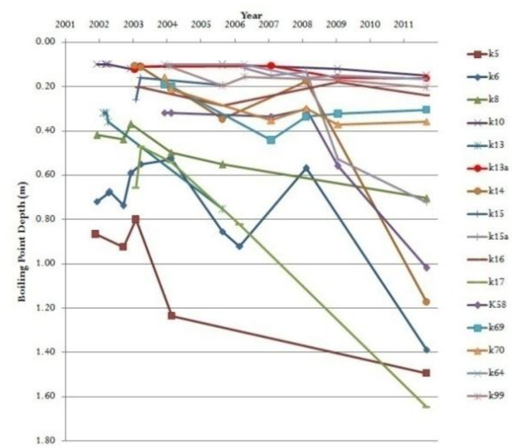

Figure 8: Level of the boiling point depth in the soil from temperature profiles.

CONCLUSIONS

The results of satellite infrared image's analysis of the Karapiti fumarole area showed that total radiative heat flux has followed a reducing trend from about 256 to 227 MW over the period of study (1990-2011). This is supported by average trends in heat loss and shallow temperature which are based on repeat ground measurements made after 2001. The results of net RHF calculations support the hypothesis of a gradual reduction in radiative heat flux from the Karapiti area since 2000. Another indirect evidence of reducing heat flux was observed to be the increasing trend of average vegetation growth and health, based on a vegetation index using the satellite imagery. Analysis of satellite infrared data provides a useful and cost-effective option for monitoring of the total radiative component of surface heat-loss from relatively large areas of steaming ground, such as at Karapiti.

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