

# Co-Seismic Water Level Changes in Koyna – Warna Region - A Wavelet Analysis

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## ABSTRACT

Koyna region in India is known to be the largest case of Reservoir Triggered Seismicity in the world and the region is seismically active till today. As wavelets are mathematical tools they can extract information from different kinds of time series. In this work the wavelet analysis has been used to see the seismic effects on the water level changes in the bore wells of the Koyna-Warna region. The 14<sup>th</sup> March 2005 earthquake with M5.1 of Koyna-Warna region has been studied for the induced co-seismic changes in bore wells. The Ukalu well has shown the maximum change in the water level since the epicenter is close to the well. The effect of epicenter distance to the wells is also studied. These results are useful in further analyzing the forecasting of the water level changes.

**Key words:** wavelet analysis, Co-seismic water level changes, Reservoir Triggered Seismicity, Koyna-Warna region

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## INTRODUCTION

The Koyna region is located in the Western part of the Indian continental plate. The Koyna-Warna region has been prone to seismic activity. Earthquakes in this region were first noticed soon after the impoundment of the Koyna reservoir behind the Koyna dam. The seismicity in this region are believed to be a reservoir triggered (Gupta and Rastogi, 1976; Talwani 1976 and Gupta et al., 1980) and this area is unique for triggering activity since the earthquakes of magnitude greater than 5 occurs even after forty five years of impoundment. The seismicity in the Koyna-Warna region has been intensively studied by several researchers (Singh et al., 1975; Rastogi et al., 1997; Gupta, 1985, 1992; Talwani et al., 1996).

Anomalous changes in water level in the bore wells have been reported by several workers. Stress may create fractures and also may be the cause for heat emission and as a result rock becomes less dense. The hydrological properties in the porous media also get effected due to the stress changes in the region. The bore wells nearby these active zones may cause changes in the water level due to boundary stress. The water level variation could be pre- or co- or post- seismic effects of earthquakes and the pre-seismic changes are generally explained in terms of changes in the crustal volumetric strain prior to the earthquakes. The co-seismic water level changes in Izu Peninsula were reported by Koisumi et al., (1999) and in Indian peninsula by Chadha et al., (2003). Latter Chadha et al., (2004) studied the relation between the static deformation and the water level changes in the Koyna-Warna region.

The water level variations in some of the bore wells are very promptly seen directly, but some are not seen directly.

In this work, the wavelet transform method has been used for analyzing the time series of the bore well water level data to understand the response of the water table with the seismicity of the region.

## METHODOLOGY

The wavelet transform is being used widely in areas of Geosciences, astronomy, astrophysics engineering, medical sciences, economics etc. Wavelet transforms are integral transforms using integration kernels called wavelets. The general representation of a wave with its corresponding wavelet is shown in Figure 1. The wavelets are scaled and translated copies (known as "daughter wavelets") of a finite-length or fast-decaying oscillating waveform (known as the "mother wavelet"). Analysis using this transformation has advantages over traditional Fourier methods in analyzing physical situations where the signal contains discontinuities and sharp spikes. The wavelet transform can be used to analyze time series that contains non-stationary power at many different frequencies (Daubechies, 1990).

The morlet wavelet is applied here to analyze the local variations of power spectrum within a single non-stationary time series. The representation of morlet wavelet with its transformation is shown in Figure 2. To be 'admissible' as a wavelet, this function must have zero mean and be localized in both time and frequency space (Farge, 1992). Even though this wavelet is a complex function, it allows us to analyze the evolution in the time-space and to calculate the phase between two time series (Soon et al., 2011).

For the Morlet wavelet transform, where the mother wavelet is:

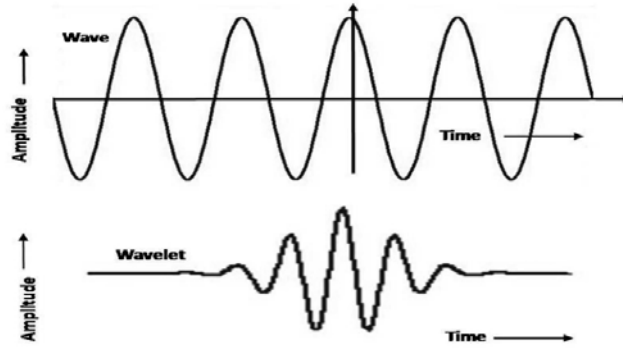


Figure 1. (a) General waves with time (b) General representation of wavelet with time.

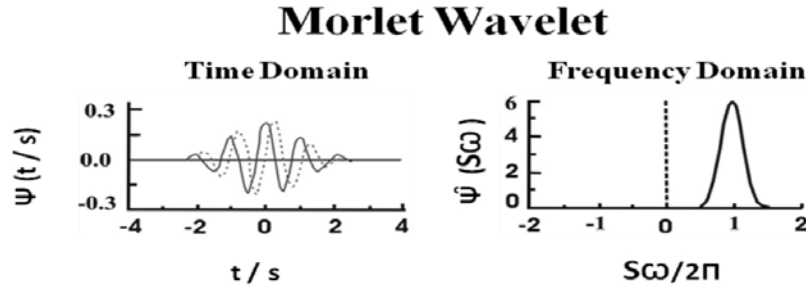


Figure 2. (a) Representation of the Morlet (mother) wavelet and (b) its transformation.

$$\Psi_o(\eta) = \pi^{-1/4} e^{iw_o\eta} e^{-\eta^2/2} \quad (1)$$

where,  $\Psi_o(\eta)$  is the wavelet value of non-dimensional time ( $\eta$ ). Here  $w_o$  is the nondimensional frequency, taken to be 6 to satisfy the admissibility condition. One condition of the wavelet transform is that the average of the wavelet itself must be zero. In practice, if we choose  $w_o = 6$ , then the error due to non-zero mean is smaller than the typical computer round-off errors (Farge, 1992). We are given a time series  $X$ , with values of  $x_n$ , at time index  $n$ . Each value is separated in time by a constant time interval  $\delta t$ . The wavelet transform  $W_n(s)$  is just the inner product (or convolution) of the wavelet function with our original time series:

$$W_n(s) = \sum_{n=0}^{N-1} x_n \Psi^* \left[ \frac{(n'-n)\delta t}{s} \right], \quad (2)$$

where, the asterisk (\*) denotes complex conjugate.

The above integral can be evaluated for various values of the scale  $s$  (usually taken to be multiples of the lowest possible frequency), as well as all values of  $n$  between the start and end time. A two-dimensional picture of the variability can then be constructed by plotting the wavelet amplitude and phase.

For set of scaling parameters  $s$ , first choose the smallest resolvable scale,  $s_o$ , as some multiple of the time resolution,  $\delta t$ . Thus  $\delta t = 0.25$  hours (i.e. 15 minutes). The smallest wavelet which can possibly be resolved is  $2\delta t$ , by choosing  $s_o = 2\delta t = 0.5$  hours. The larger scales (longer periods) are chosen as power-of-two multiples of this small scale,

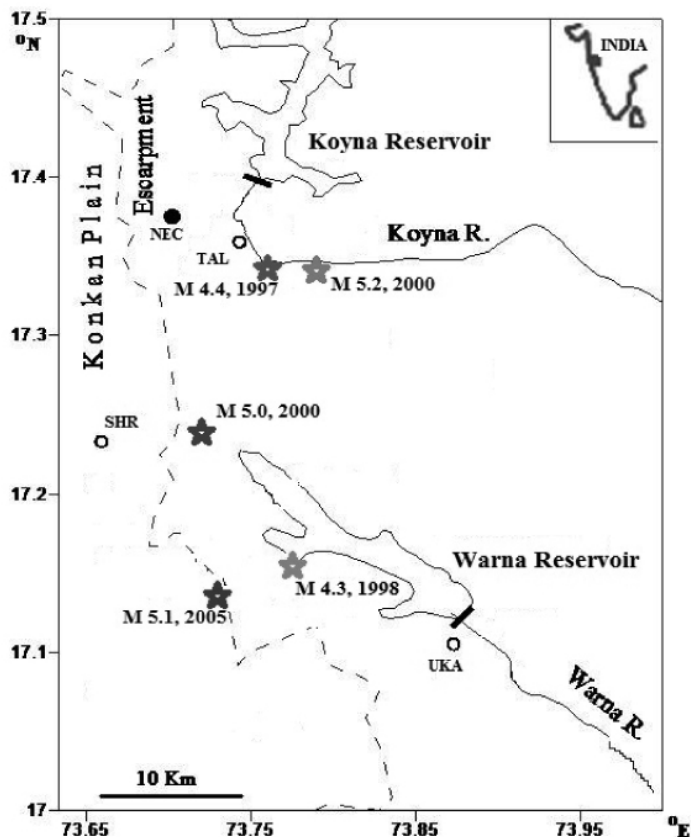
$$s_j = s_o 2^{j\delta}, \quad j=0,1,\dots,J \quad (3)$$

$$J = \delta j^{-1} \log_2 \left( \frac{N\delta t}{s_o} \right) \quad (4)$$

Here  $j$  determines the largest scale and it is considered as 56,  $\delta j$  is 0.125 and  $N = 506$  respectively. The cone of influence (COI) is the region of the wavelet spectrum outside which the edge effects become important (Torrence and Compo, 1998). Wavelet Power Spectral Density (WPSD) is calculated for each parameter; the black thin lines in Wavelet Power Spectra of Figure 4 and Figure 5 mark the 95% confidence interval or boundaries of COI.

## RESULTS AND DISCUSSIONS

Twenty one bore wells were drilled during 1995 – 1998 in the Koyna-Warna region at depths ranging from 990 to 250 m to monitor the variation of pore pressure in and



**Figure 3.** Location of the Koyna-Warna region. (Circles indicate the location of the bore wells, open circle is for open well and closed circle for closed well. Stars indicate the location of earthquake epicentres).

around the seismically active area of that region (Figure 3). The time series analysis on the water level data from some of these bore wells for the month of March 2005 was conducted, since on March 14, 2005 magnitude 5.1 earthquake had occurred in Koyna-Warna region and the epicenter of the event was close to the Warna reservoir. The focal mechanism was that due to a normal fault. The co-seismic effect of the event was observed in some of the bore wells. The sudden fall in the water level seen in Ukalu well close to the Warna reservoir is very significant. Time series analysis using the wavelet theory was carried out and the power spectrum of the water level data in some of the bore wells calculated. The Morlet wavelet transform was used for the bore well water level time series data from 1<sup>st</sup> March 2005 to 31<sup>st</sup> March 2005. Figure 4 shows the power spectrum of the bore well water level data. From Figure 4 it is very clear that the peaks in the transform domain and these peaks are correlated with the time of the earthquake of 14<sup>th</sup> March 2005 with magnitude 5.1. The variation in the water levels in the Shringarpur bore well is not significantly revealed in the original time series, but a small peak is seen in the power spectrum which correlates at 14<sup>th</sup> March.

In the original time series of Nechal well water level data a sudden rise in the water level was observed at the time of the event. The numerical results also show that there is a small variation in the original time series of Taloshi bore well water level data, but this is not reflected in the transformed power spectrum.

To see the importance of the wavelet transform method on the water level data time series the transformation has been applied to the bore well water level data at different times and also at different bore wells. The time series analysis was also taken up on the data from the earlier events reported in April 1997, Feb. 1998, June 1999, March 2000 and Sep. 2000 with magnitude greater than 4 in Koyna-Warna region. The spectrum has been calculated for the Ukalu well using the wavelet transform. The original data after removing the tidal effects (upper) and the spectrum (lower) is shown in Figure 5. Though the co seismic effects in the bore well water level data in the time domain are not noticeable in the figure (Figure 5) they appear prominently in the power spectrum of April 1997 data. The data of Feb. 1998, March 2000 and Sep. 2000 was also analysed in a similar way, the results of which are also shown in the same figure. It is clear from

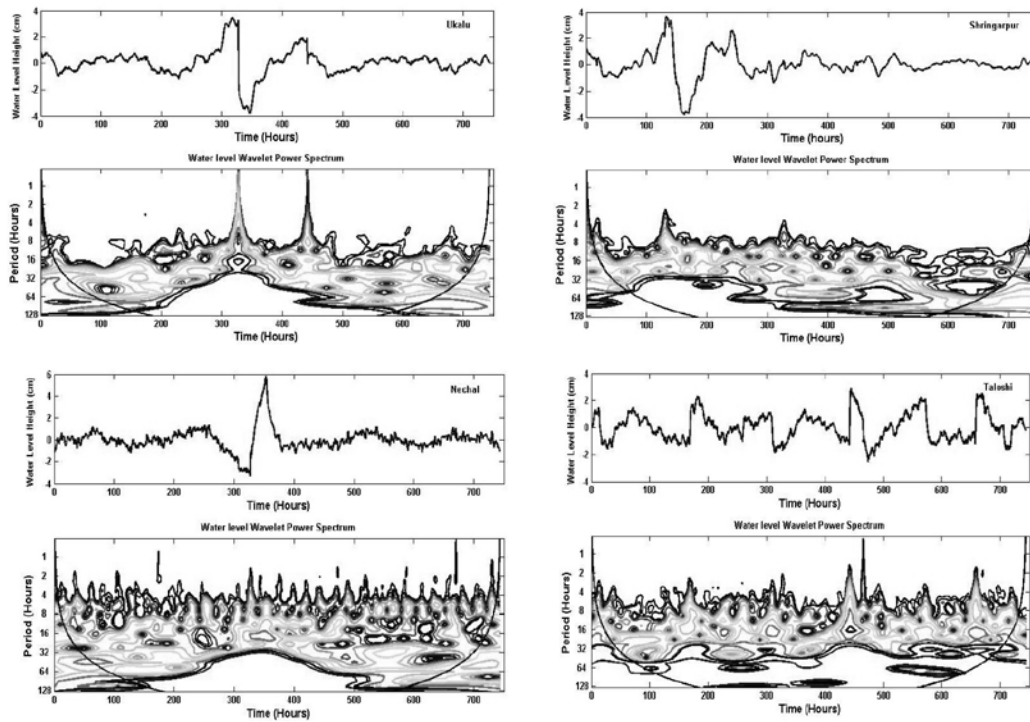


Figure 4. Water level variation (above), Power spectrum (below) in different bore wells from 1 March 2005 to 31 March 2005 (a) for Ukalu (b) Shringarpur (c) Nechal and (d) Taloshi.

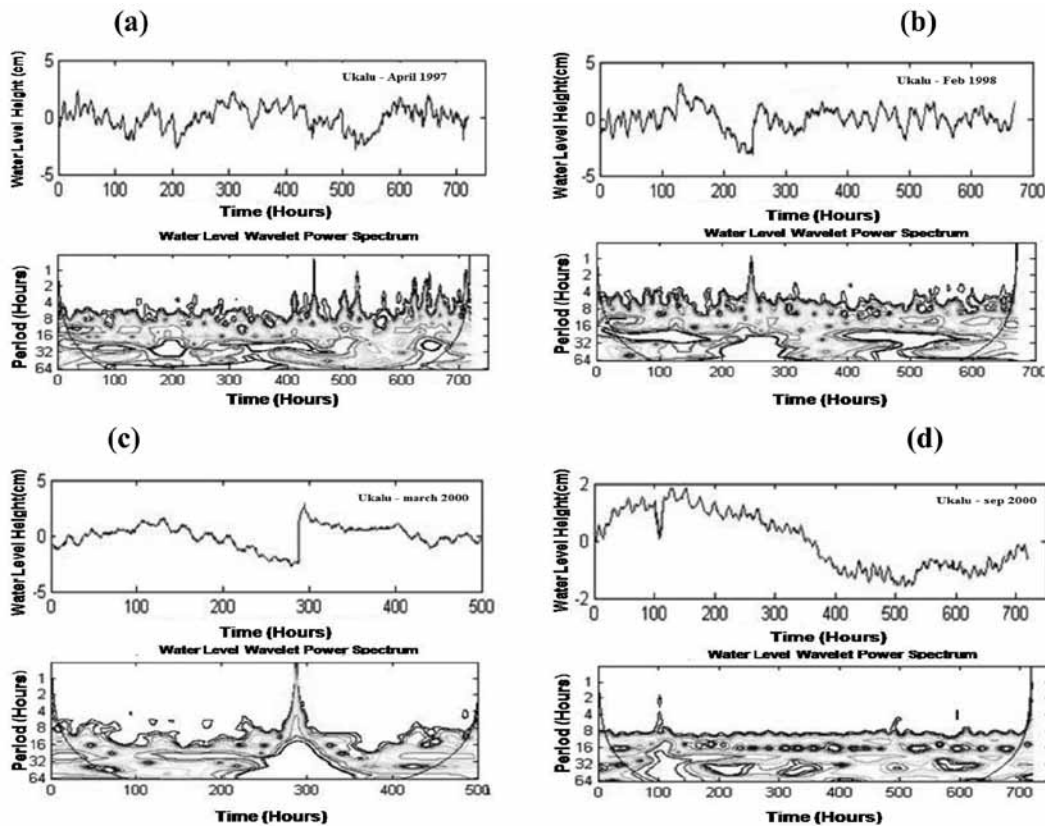
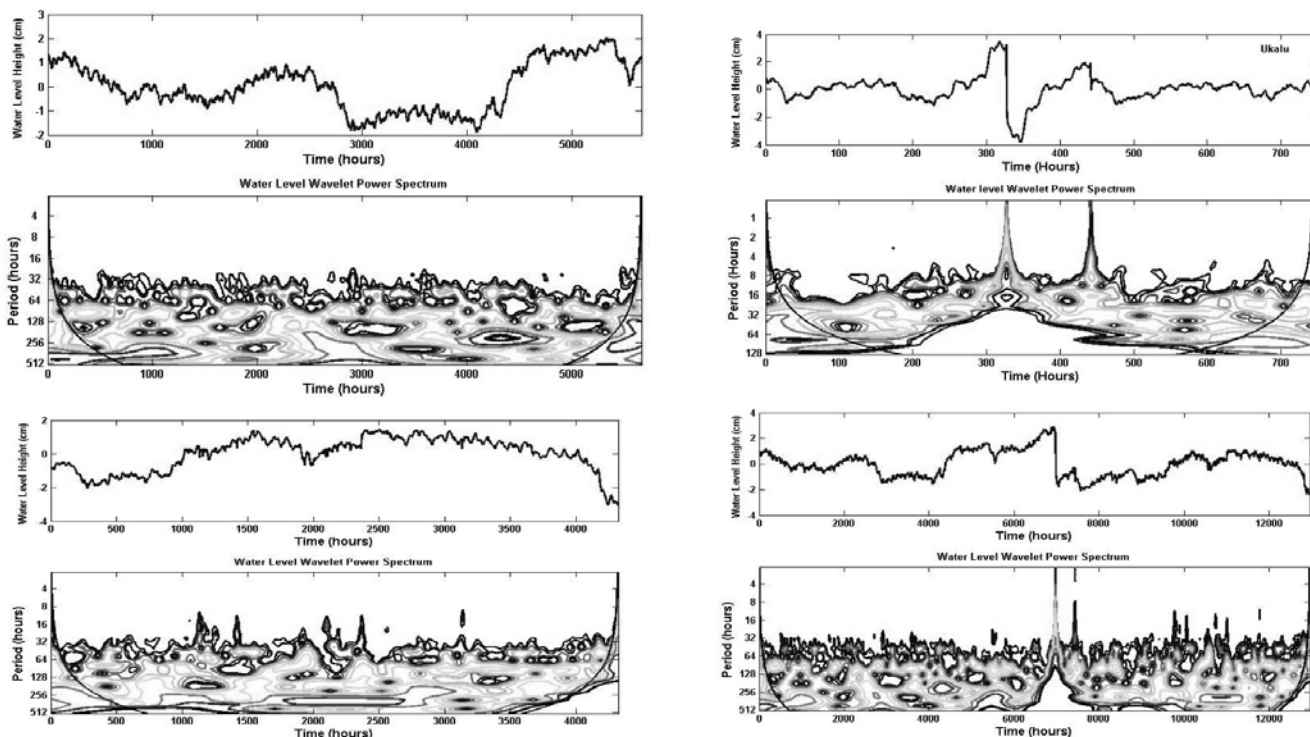


Figure 5. water level variation (above), Power spectrum (below) for Ukalu well data (a) April 1997 (b) Feb. 1998 (c) March 2000 and (d) Sep. 2000.



**Figure 6.** water level variation (above), Power spectrum (below) for Ukalu well data from January 1<sup>st</sup> 2005 to may 31<sup>st</sup> 2005: (a) January 1<sup>st</sup> 2005 to Feb 29<sup>th</sup> 2005 (b) march 2005 (c) march 31<sup>st</sup> 2005 to may 31<sup>st</sup> 2005 (d) January 1<sup>st</sup> 2005 to may 31<sup>st</sup> 2005.

**Table 1.** Water level variation in different wells due to 14th March 2005 event.

Name of the Well	Water Level Variation (cm)
Ukalu (UKA)	-14
Shringarpur (SHR)	-3
Nechal (NEC)	9
Taloshi (TAL)	3

the figure that the co-seismic effects of the earthquakes in Koyna-Warna region are very distinctly revealed in the wavelet spectrum of the water level data.

Figure 6 shows the spectrum for different time periods; (a) shows the period from Jan. to Feb. 2005 i.e., before the event, (b) is for the month of March. 2005 i.e. at the time of event and (c) shows from April. 2005 to May. 2005 i.e. after the event. (d) Shows the time period from Jan. 2005 to May. 2005. From this Figure, it is very clear that a sudden peak in the spectrum which is well correlated with the time of event in Figure 6 (d) is more distinct when we consider the small window close to the time of the event (Figure 4 (a)).

In Table 1 are furnished the variation of water levels at different locations at the time of the event for 14<sup>th</sup> March 2005. Though no significant relationship could be established between variation in the bore well water levels and the distance between the epicenter and the bore well

it appears that the water level in the bore wells decreases when located in the zone of extension forces and the water level rises if located in the zone of compression forces.

## CONCLUSIONS

Analysis of water level data using wavelet transformation for some of the bore wells nearer to Koyna-Warna region has shown co-seismic variation due to 14<sup>th</sup> March 2005 Koyna earthquakes. The power spectrum calculated using the wavelet transform brought out the correlation between the water levels in bore wells and occurrence of an earthquake. In Ukalu the water level in the well nearer to an event showed prompt effect during earthquake. Analysis of the Ukalu well at different events of Koyna-Warna region show co-seismic water level change in the transformed domain very promptly but are not seen in the original time domain.

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## Compliance with Ethical Standards

The authors declare that they have no conflict of interest and adhere to copyright norms.

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