

RAINFALL PATTERNS OVER THE GNANGARA MOUND

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Abstract

Fully accepting climatic change, we investigate and interpret observations of cycles in the regional rainfall around Perth and the Gnangara groundwater mound. The data shows that the deterministic portion of the rainfall record is cyclic and may be up to 40% of the variance. The frequency analysis of around 100 years of rainfall records reveals cyclic patterns with periodicity of ~9 years and ~30 years. The insignificant linear decrease of ~0.5mm/year may be added but it decreases the statistical likelihood and is more likely a portion of a cyclic trend with a period of ~120 years. The analysis showed no abrupt, exponential, linear or other monotonic decrease in rainfall at or near the coast but the increase of rainfall with distance from the coast is decreasing with time.

Rainfall received in the Perth region and the major superficial aquifer is thought to have been decreasing the past 28 years and decreasing even more in the past 3 years. The underlying scale and spatial variation connects with the Millennium Ecosystem Assessment and Ramsar Convention Wise Use of Wetlands. We suggest that not only evapotranspiration but also rainfall, recharge, floods and droughts are significantly influenced by the presence and health of wetlands and woodlands.

Keywords: cycles, rainfall, trends, patterns, climate change, Swan Coastal Plain, wetlands, Gnangara, mound, aquifer, lakes, recharge, evapotranspiration

Introduction

The importance of climate change and the global and regional challenge of securing an appropriate policy response has necessarily preoccupied policy and research attention (Ruprecht 1996; Sadler et al 1988). However Ruprecht (1996 p 3) also acknowledged that "interdecadal variability of the natural climate system, at least as much as interannual fluctuations, will tend to mask anthropomorphic changes in climate". Different paths are being taken to unravel the understanding of climatic drivers, but some initial presumptions may well limit our judgements.

Over the last century groundwater levels of the Gnangara Mound have reflected long-term rainfall trends, on which landuse change and abstraction impacts are superimposed (Vogwill et al. 2006). The Gnangara mound is the most significant source of water in Western Australia; it supports a variety of horticultural, agricultural, industrial, domestic and recreational needs; greater than 300 G/L per year is abstracted. The mound also underpins numerous groundwater dependent features (many with international recognition) that support a range of social, cultural and environmental values. Groundwater levels on the Gnangara Mound are declining (>500 GL reduction in storage) and negative impacts are increasing in numbers and intensity. One of the areas of documented impacts is the Wanneroo area (Water and Rivers Commission 2004). Lake levels are expressions of the water table and are declining; this has exposed acid sulphate soils and created water quality deterioration and negative ecological impacts.

There is clear evidence of substantial fluctuations in levels of the Wanneroo wetlands during the Holocene. This is due to rainfall variation alone (McHugh 2004); however, the work was

unable to look at rates of decline, only magnitudes, due to project constraints. Wetlands also respond to variations in the balance of groundwater discharge into the wetland, as well as evaporation and groundwater outflow. Abstraction and landuse changes are also important.

Commander and Hauck (2005) state that: “changes in recharge...are reflected in water levels of the shallow aquifer, and the wetlands expand or contract to vary the amount of groundwater discharge by evaporation. Over the last century groundwater levels on the Gngangara Mound have reflected the long-term rainfall trend”. Their analysis in Figure 1 is based on a cumulative deviation from the mean (CDFM); it shows the cumulative rainfall and cumulative groundwater levels marching along together, both substantially decreasing with time. One must remember that this does not apply to all of the Gngangara Mound and definitely not to groundwater levels in Wanneroo. Also the CDFM analysis is based on a prior judgment about the average. If, indeed, the average were defined based on recent years, the plot would show an increasing but slowing trend; hence, here we avoid the use of an analysis based on CDFM.

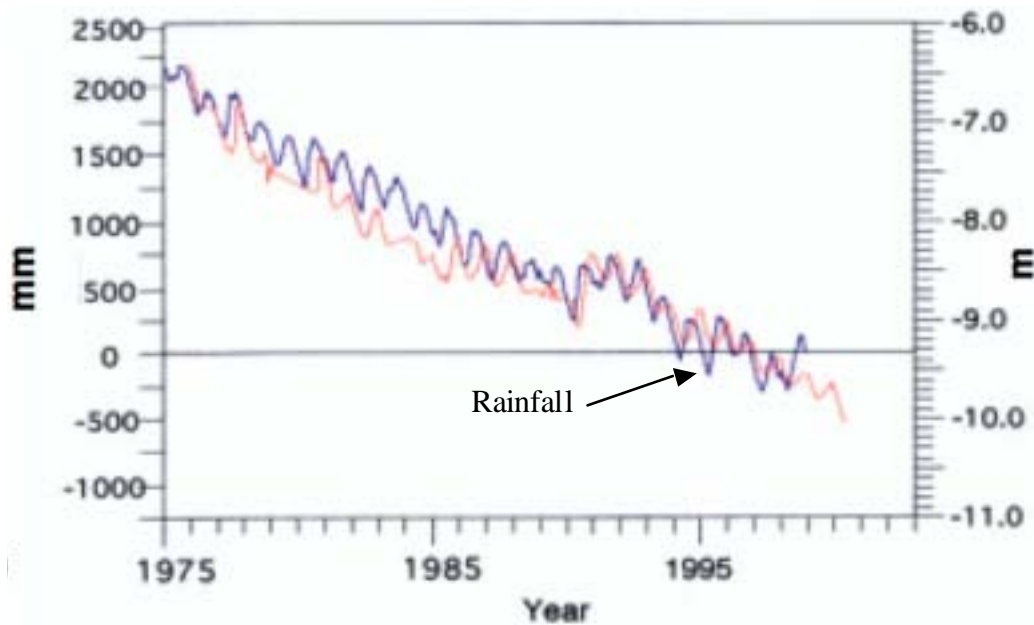


Figure 1 Rainfall (left scale in mm) and depth to groundwater (right scale in m) from Commander and Hauck (2005)*.

As identified in Yesertener (2002, 2003), there are variable rainfall patterns across the Swan Coastal Plain and a dominant impact across the Gngangara Mound, which is approximately 20-25km west-east. Rainfall declines and landuse are important in the central part of the Gngangara Mound, but around the margins where groundwater discharge occurs into lakes, rivers and the ocean, pumping impacts can dominate (Ibid 2003; Vogwill et al. 2006).

Here we use Occam's razor, apply a special frequency analysis, and extend the data set backward to around 1890. The analysis is similar to that applied by Scott et al. (1992) to turbidity data 1979-1984; in that case roughly 10% of the variance was explained by a

* One of several publications with the Indian Ocean Climate Initiative IOCI. See for examples, the notes on rainfall in the SW:

http://www.ioci.org.au/publications/pdf/IOCIclimatenotes_5.pdf

http://www.ioci.org.au/publications/pdf/IOCIclimatenotes_6.pdf

frequency of about 3 yrs, 20% was explained by an annual variation, other significant frequencies accounted for another 10% and there was about a 10% increase in turbidity per year.

The SILO data, Figure 2, shows a large amount of similarity across three different stations, part of which is an artefact of the interpolation technique (kriging) used to generate the data (Jeffrey et al. 2001).

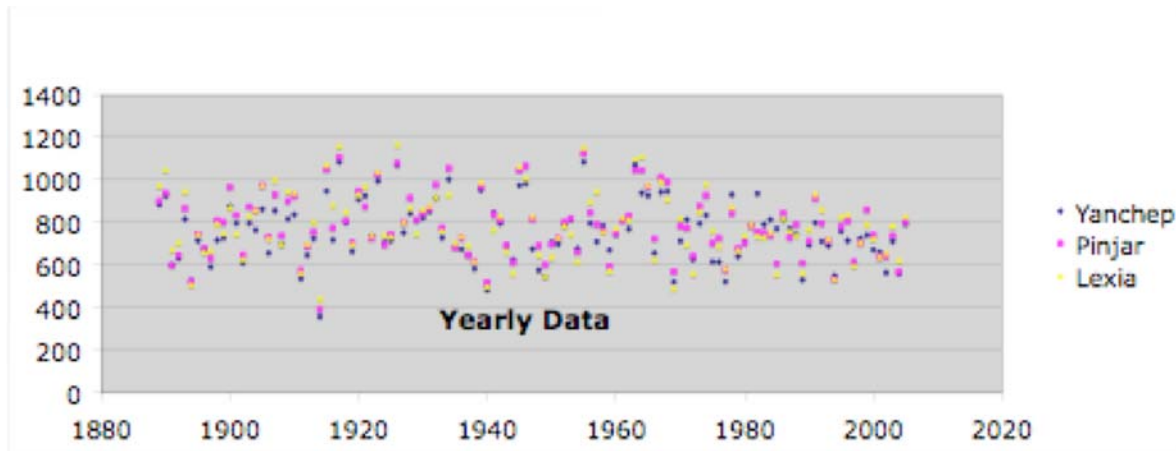


Figure 2. Yearly rainfall data from SILO/Data Drill through 2005.

Method

Running Averages: Three standard data sets from SILO/Data Drill were used to represent validated and statistically weighted meteorological rainfall records at locations over the Gngangara groundwater mound. The data are used to calibrate water balance models; they broadly cover the area of infiltration and surface recharge in the Perth Urban Water Balance, as used for the assessment of Perth's major groundwater resource. The data are presented as a series of averages, with 3, 5, 10 and 20 year running means.

Regression Equations: The specific analysis in Excel starts with a guess regarding two (or three) arbitrary frequencies and (perhaps) a linear trend, power function or specially placed exponential. A multivariate linear regression with LINEST produces the required coefficients as well as statistics. The process is repeated with other frequencies and the combination that produces the smallest sum of square of the deviations (residuals, measured minus calculated) is selected. Specifically one maximises the Coefficient of Determination CoD; the Tools/Solver in Excel makes this straightforward but initially the guessing is done by hand, to get a 'feel' for the operation and generate 'seed' values.

Results

Clearly, cyclic patterns appear that have periods longer than 3 years; however, an eyeball assessment doesn't show a significant trend in the more than 100 year record. The regression equations are similar. All show a small trend, less than 1 mm/yr, with periods of around 45 yrs and 9 yrs. The Coefficients of Determination CoD values suggest that up to 17% of the variance in the data can be considered either cyclic or a part of the small linear trend. There are questions, however, because of the composited nature of the data from SILO/Data Drill.

Data Drill

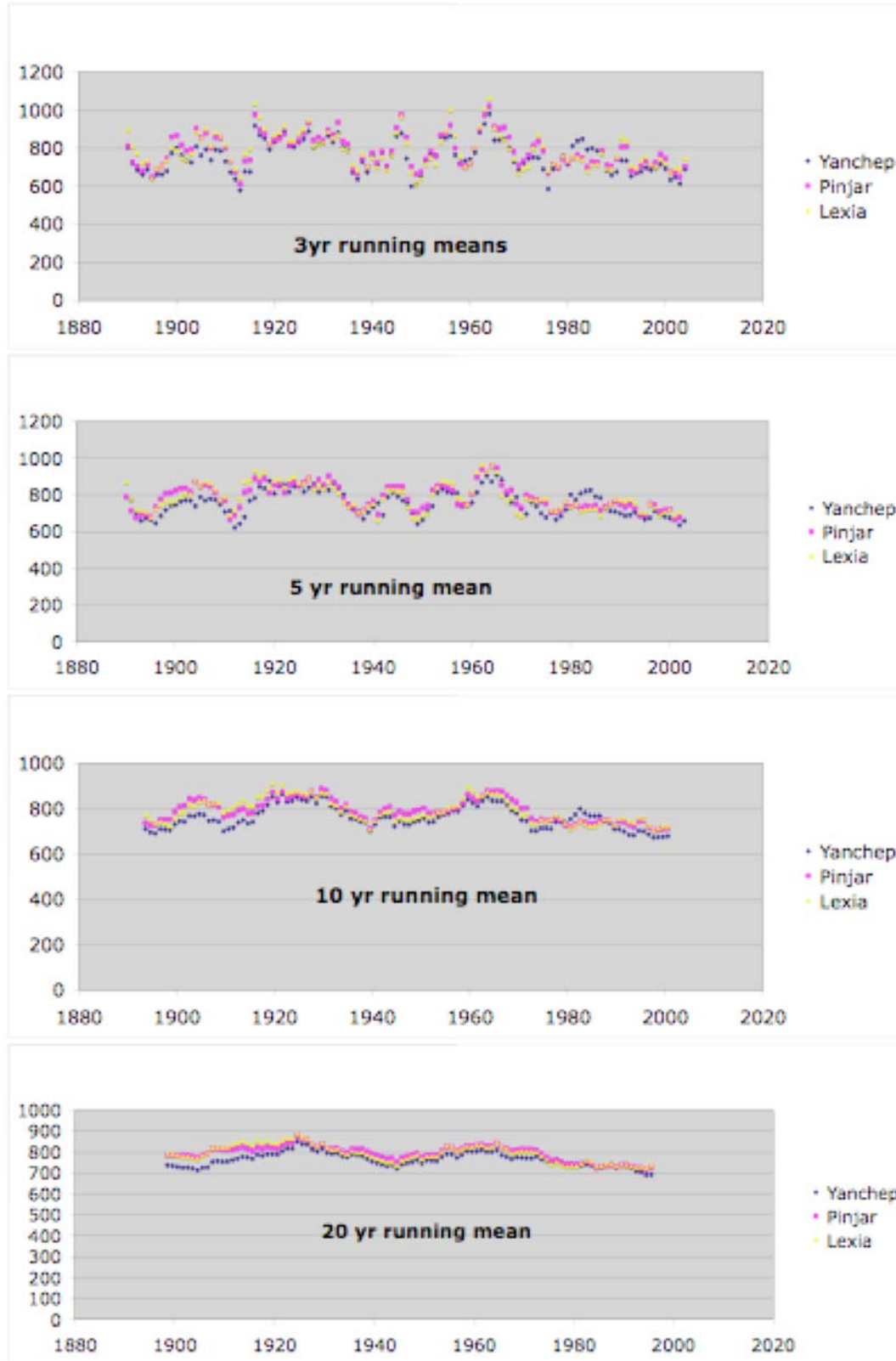
The standard data sets from Yanchep, Pinjar and Lexia are generated by the SILO/Data

Drill process and are 'smoothed' extrapolations of real data. Details are available from SILO:

<http://www.nrm.qld.gov.au/silo/datadrill/>

<http://www.nrm.qld.gov.au/silo/documentation/RainfallInterpolation.pdf>

It is an interpolation technique (Jeffrey et al. 2001) which uses monthly rainfall values



Figures 3. Running means from Yanchep, Pinjar and Lexia. Data from SILO/Data Drill. The averages are limited at the ends by the data points available.

extrapolated with simple kriging, a process where interpolated data is raised to a power fitted to a normal distribution. The mean, variance and fractional power vary spatially; these parameters form a trivariate thin spline with latitude, longitude and altitude as independent variables. An observed value of monthly rainfall forms a normalized residual using the power, mean and variance. As such there will be some kriging related smoothing and inaccuracies (Isaaks and Srivastava 1989), dependent on the location of long-term records with respect to the interpolated locations.

Table 1. Fitting of the SILO data

		Regression Equation	CoD
Yanchep	31° 33' S Lat. 115° 42' E Long.	$1472.3 - 0.365 t + 47.6 \cos(2\pi t/47.4 + 2.72)$ $+ 44.16 \cos(2\pi t/9.23 + 1.8)$	0.12
Pinjar	31° 33' S Lat. 115° 51' E Long.	$1987.1 - 0.614 t + 44.9 \cos(2\pi t/47.5 - 2.63)$ $+ 52.0 \cos(2\pi t/9.25 - 1.73)$	0.136
Lexia	31° 45' S Lat. 115° 57' E Long.	$2462.3 - 0.857 t + 55.3 \cos(2\pi t/44.7 + 0.19)$ $+ 60.5 \cos(2\pi t/9.36 + 1.08)$	0.166

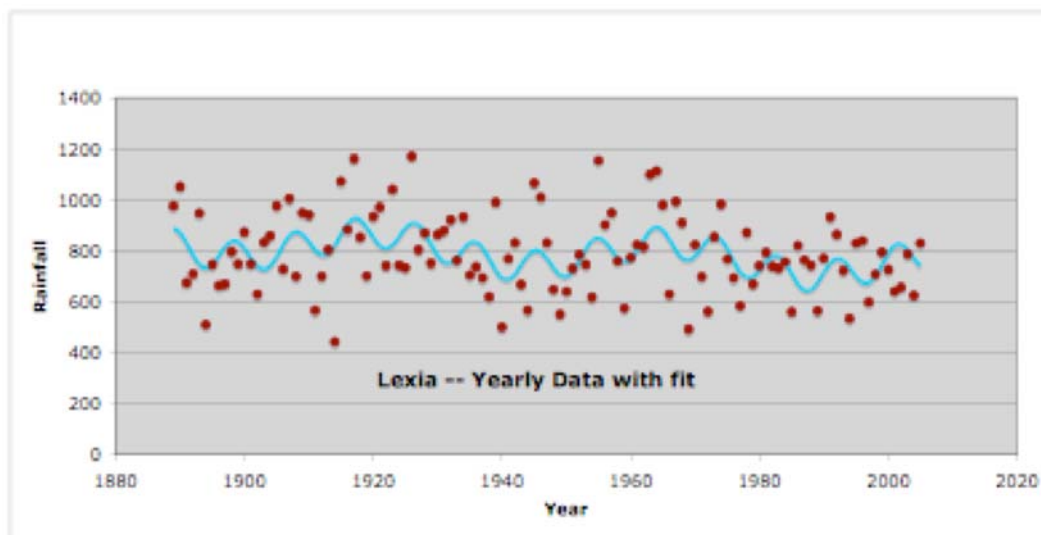


Figure 4. Fitting of the data from Lexia. Note the scatter seems less around 2000.

Jeffrey et al. (2001) and the SILO project are forthcoming with the possible inaccuracies and limitations of the SILO data. Only simple kriging was used due to data constraints. With only simple kriging, it is preferred that the technique be used on data sets with a constant mean and no underlying trends; universal kriging should be applied to data with a deterministic trend in the underlying data (Avalos and Gonzalez 2006).

Clearly where the impacts of climate change on rainfall is concerned, with underlying trends being the focus of analysis, the use of kriged data, particularly simply kriged data, are concerning; one needs to be careful. The use of actual data is preferable, but not always possible.

BoM Data Sets

Hence four real rainfall records from the Bureau of Meteorology BoM were processed; Perth, Rottnest, Gingin, and Wilgarrup. The 'stations' are near the west coast except Wilgarrup which is about 350 km southeast of Perth. All the stations have been variously altered with

time; Wilgarrup and Gingin are the most contiguous and consistent*. Perth has, perhaps, the worst record because the station has been moved about 4 times. Rottneest Lighthouse was closed in 1995 and the statistics have been altered.

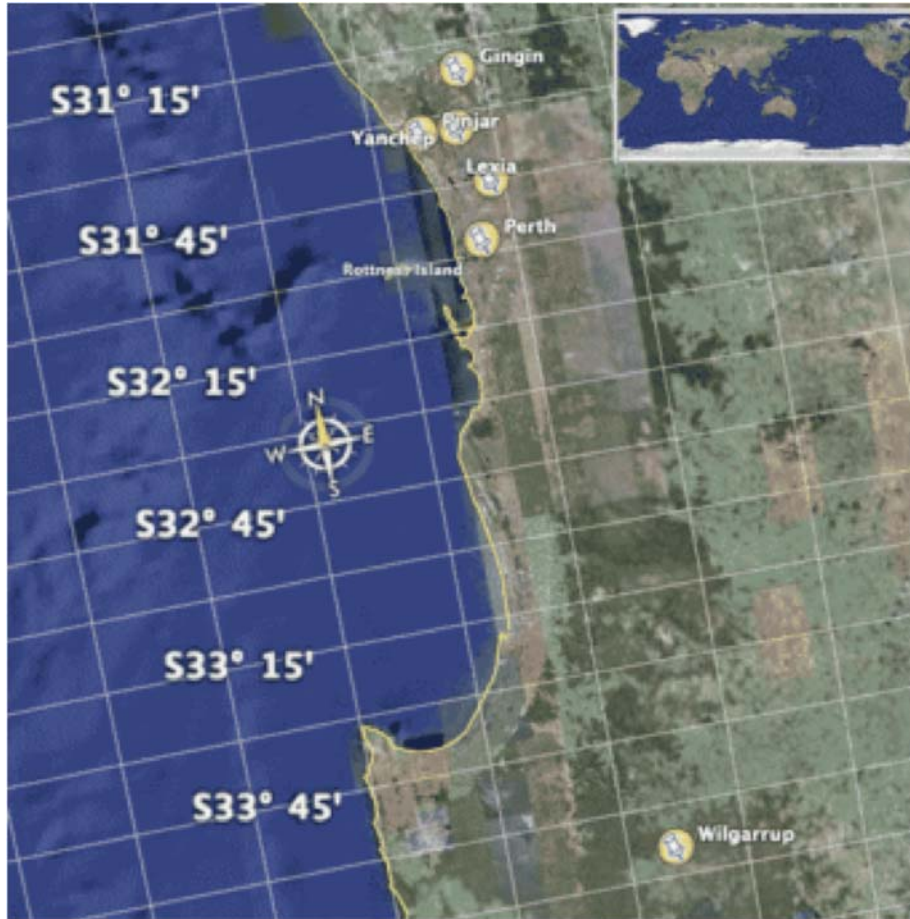


Figure 5. Locations of the various stations as seen on earth.google.com

Table 2. Fitting with a linear trend and two frequencies

		Regression Equation	CoD
9034 Perth	31° 57' S Lat. 115° 52' E Long.	$2036.3 - 0.606 t + 32.2 \cos(2\pi t / 32.4 - 2.35) + 57.8 \cos(2\pi t / 9.28 + 2.16)$	0.108
9038 Rottneest	32° 00' S Lat. 115° 30' E Long.	$2745.1 - 1.05 t + 73.1 \cos(2\pi t / 33.2 + 0.38) + 37.3 \cos(2\pi t / 9.42 + 2.4)$	0.200
9018 Gingin	31° 21' S Lat. 115° 54' E Long.	$2462.3 - 0.857 t + 55.3 \cos(2\pi t / 44.7 + 0.19) + 60.5 \cos(2\pi t / 9.36 + 1.08)$	0.190
9619 Wilgarrup	34° 09' S Lat. 116° 12' E Long.	$6478.0 - 2.845 t + 56.5 \cos(2\pi t / 29.6 + 0.68) + 64.6 \cos(2\pi t / 9.19 + 2.72)$	0.280

Still, all the data are similar to the results from the SILO data (see Table 2). Importantly, 10 to 20% of the variance is explained by a cyclic trend; Wilgarrup, 28%. All the stations show a cyclic pattern of ~9 years; Perth, Rottneest and Wilgarrup, a longer cyclic period of ~30 years; Gingin, ~45 years. Gingin shows a 1 mm/yr downward trend; Wilgarrup, 2.8 mm/yr. The effect is, perhaps, best summarised in Figure 6, as an effect from the west coast.

* private communication with Alan Scott, Bureau of Meteorology, Perth.

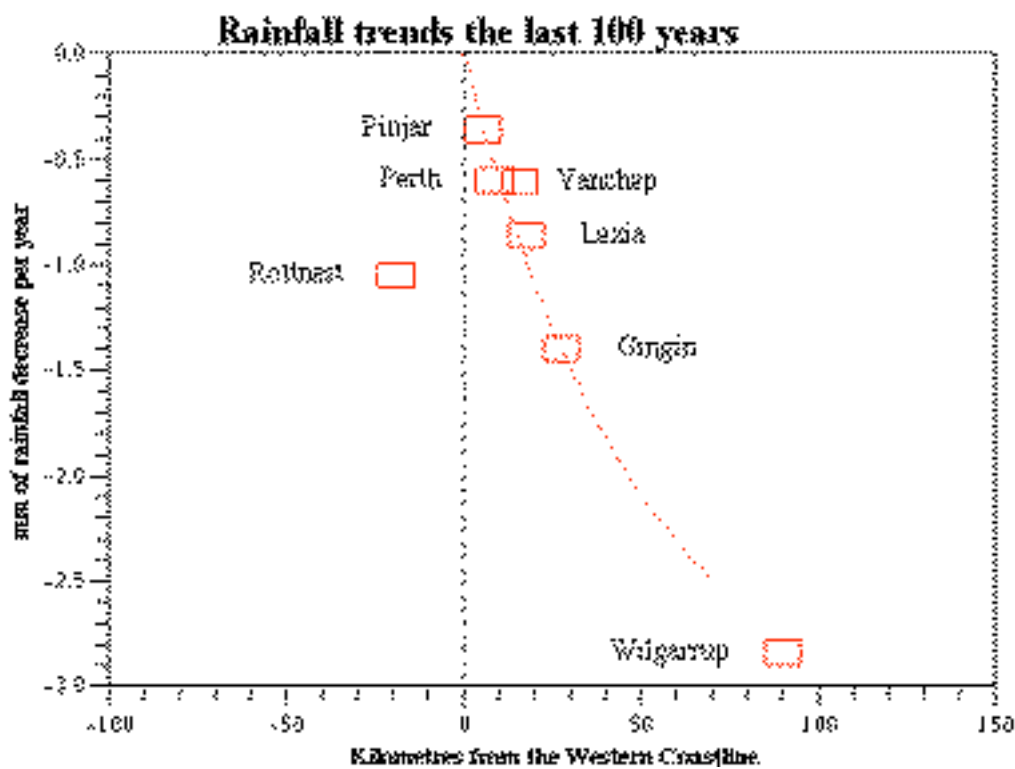


Figure 6. A plot of the Regression results, the linear trends, how they vary with distance from the western coast

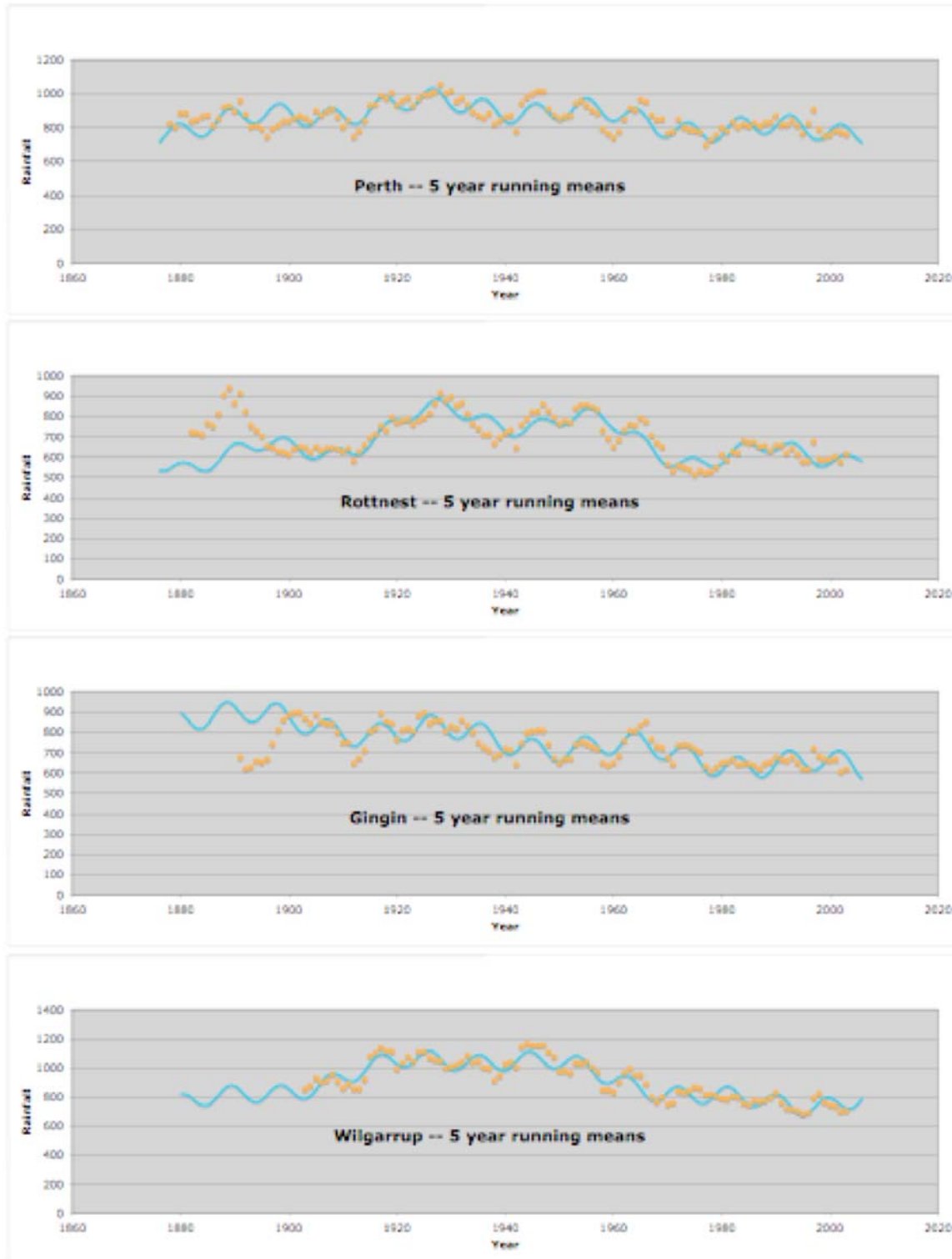
The dotted line suggests a trend with about a 20 km e-folding distance. It seems there is little or no linear trend at the coast of Western Australia. The relation to the coast is relatively unclear however. Firstly, the coast is not just a straight line; secondly, in reference to the Scott Coastal Plain and the southern ocean, Wilgarrup is in a similarly situation to Gingin.

Three Frequencies

Further, the data were fitted with other forms, including power functions and arbitrary exponential changes. None of these improved the fit; however, including another longer cycle did improve the fit, as illustrated in Table 3 and Figures 7. Note that the linear trend is missing.

Table 3. Fitting with three separate frequencies

		Regression Equation	CoD
9034	Perth 31° 57' S Lat. 115° 52' E Long.	$860.49 + 39.8 \cos(2\pi t / 32.206 + 1.4)$ $+ 58.36 \cos(2\pi t / 9.429649 - 2.0015)$ $+ 76.64 \cos(2\pi t / 126.4943 - 1.566)$	0.217
9038	Rottnest 32° 00' S Lat. 115° 30' E Long.	$701.3 + 66.62 \cos(2\pi t / 31.0863 + 0.288)$ $+ 34.968 \cos(2\pi t / 9.4013 - 0.15177)$ $+ 107.44 \cos(2\pi t / 99.233 + 2.995)$	0.364
9018	Gingin 31° 21' S Lat. 115° 54' E Long.	$693.08 + 40.09 \cos(2\pi t / 34.8922 - 1.808)$ $+ 54.92 \cos(2\pi t / 9.446178 + 0.54562)$ $+ 301.9 \cos(2\pi t / 800 - 1.3436)$	0.267
9619	Wilgarrup 34° 09' S Lat. 116° 12' E Long.	$914.26 + 38.25 \cos(2\pi t / 31.8473 - 1.6551)$ $+ 58.476 \cos(2\pi t / 9.1793 + 1.141)$ $+ 156.56 \cos(2\pi t / 112.27 - 1.447)$	0.415



Figures 7. Fitting of Cyclic regression lines to smoothed data from the Bureau of Meteorology.

Table 3 shows that the CoD values are increased by about 0.1 by using another, longer cycle, around 120 years. The Figures 7 show that the algorithms form a remarkable fit,

following of the running means except for a few excursions. With as much as 36% of the variance explained at Rottneest, one is tempted to use the cyclic trends in forecasting; the same with Wilgarrup, with 41%. One can't help but wonder if a lot of the discrepancy is simply the vagaries of politics and data collection.

Discussion

Cycles and Trends

There is change; in global, regional and local climate and rainfall. Since around 1975, Perth regional coastal rainfall has been reducing. The regional coastal rainfall change is seen in the removal of nearly all the summer rainfall, and about 15% of the early winter rains, and has produced a 60% reduction of runoff into dams in the last few years*. However, analysis of the rainfall pattern at the coast shows no indication of any once-off changes, as expected the last 100 years or more due to the activities of European man. Current regional coastal rainfall changes can instead be accommodated into a cyclic pattern with two or three different frequencies, around 9 years, 30 years, and, perhaps, 120 years.

The stochastic model applied to the data uses mathematical linearity and considers the rainfall pattern as a sum of two terms; one is random; the other is deterministic. Fitting the data from the Gnangara mound and several nearby meteorological stations shows that as much as 40% of the variance is deterministic.

Of the deterministic part, the model considers two primary patterns: one is cyclic; the other stepped, exponential, linear or other not repeated, once off pattern. Figure 12 presents a schematic of a simplest arrangement with a cyclic pattern superimposed on a linear trend. Simply put, the linear trend or non-cyclic pattern is expected of man's activities**. The cyclic component, however, is expected from most natural dynamical processes of the atmosphere, the ocean and tides. The present analysis points to a lack of the linear trend at or near the coast.

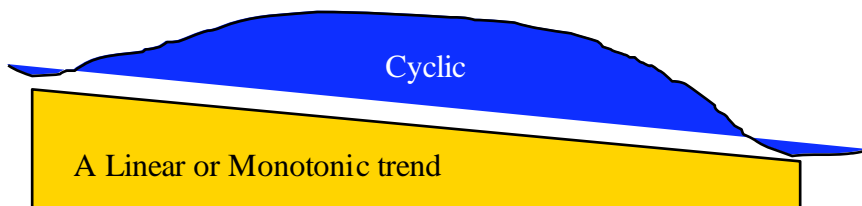


Figure 12. Schematic showing the superposition of a cyclic and continuous trend

The maximum likelihood technique predicts that any linear trend near the coast is less than a mm of rainfall a year. Also, the pattern is not properly described by fitting with a function of a higher power, including an arbitrary exponential. There is, however, an improved fitting when ~120 year cycle is added to the pattern or replaces the linear trend. In the case of the historically contiguous data from Wilgarrup, 90 km to the SSE, the three cyclic frequencies of 9 years, 33 years and 120 years contribute 41% of the variance. This is a good fit.

It remains that rainfall decrease experienced on the Gnangara mound has at least two possible causes:

- 1) The rainfall increase as one goes inland from the coast (the first ~50 km) has decreased, a deterministic effect.
- 2) Rainfall events that generally happen during storms and during summer are

* Brian Ryan, Personal Communication. Runoff reductions may also be related to changes in catchment vegetation.

** The effect could come from natural activities such as earthquakes, volcanic eruptions or even events produced by collisions with comets

infrequent, a more or less random effect.

As in the other parts of this paper, the following discussion ignores the random component in favour of the systematic effect 1). This is not to diminish the contribution of 2) but to simply avoid a degree of unpredictability and contribute as we can.

Local and Inland Rainfall Change

The increase in rainfall as one goes inland from the coast is important; it amounts to approximately a doubling of the rainfall from off the coast (Rottnest) to the peak of rainfall (Mt. Dale) (Seddon 1973). The analysis may well suggest that the increase is decreasing with time; a marked decrease with an e-folding distance of ~25 km. The local rainfall increase has been recognised in the past as a sub-synoptic effect that exists because of the orography of the coastal plain and scarp Gentilli (1998), but it also correlates with the location and extent of Perth's extensive wetlands (Hill et al 1996). Isohyets prepared over the Ellen Brook catchment near Gingin also show a remarkable correlation with vegetation clearing history which has been mapped (Hammond and Mauger 1985a, 1985b). Wetland heath and woodland vegetation create roughness, transpire and are a source of atmospheric water; but as well they release particles and chemicals that are effective in rain production in both warm and cold clouds.

Lyons (2002) and Esau and Lyons (2002) show documented effects of the rabbit-proof fence in WA. As seen from space, the placement of the fence has changed the upward moisture and heat transport and results in quite different cloud activity and rainfall. The increasing development of Perth, removal and changing of vegetation, hard bitumen and concrete surfaces, traffic and heat sources create heat islands* which alter air flow, heat and moisture conveyance, and cloud activity (Oke 1982). The Kwinana industrial area and Perth may create a plume that produces large clouds that are ineffectual in producing rain**. The presence of wetlands, woodland and forest vegetation increases the atmospheric moisture, upward moisture transfer and, ultimately, rainfall. Urban development, with pollution and heat island effects, also reduces moisture and creates larger numbers of condensation nuclei and colloidally stable clouds. The result is reduced rainfall, particularly downwind, in this case probably in the catchments in the hills.

Land Cover CO₂ Warming

Further, modelling by Pitman et al. (2004) and Pitman and Narisma (2005) considered land cover change in the South West relative to CO₂ warming; they found that up to 50% of the effect of reduction of South West rainfall in the last half of the 20th century was caused by land cover changes. This comes from reduced surface roughness, increasing moisture divergence, increased horizontal wind magnitudes and suppressed vertical velocities. They suggest: "Our results indicate that rainfall over southwest Western Australia may be returned to the long-term average through large-scale reforestation, a policy option within the control of local government. Such a program would also provide a century-scale carbon sink to ameliorate Australia's very high per capita greenhouse gas emissions."

The Millenium Assessment, Ramsar Convention and Global Climate Change

The Millenium Assessment (2005) recognises global, regional and local drivers and their

* http://en.wikipedia.org/wiki/Heat_island

** Bigg and Turvey (1978) during flights around Australia intensively sampled aerosols and condensation nuclei downwind of Perth and observed colloidal 'fumulus' clouds. Larry Radke found that emissions of large numbers of particles may remove cloud activity (Hobbs 1985; 1988); however, the presence of appropriate hygroscopic particles may increase rainfall (Ferek et al. 2000). Vegetation is also known to emit particulates and compounds, terpenes, that affect clouds and produce rain.

effects at all levels on rainfall and water management. The Ramsar Convention Wise Use of Wetlands Guideline Handbook No 12 on Water Allocation and Management (Ramsar 2004) shows the need to maintain the cycling of water through forests and vegetated wetlands to reduce the possibility of the positive feedback cycle of desertification that follows when water is no longer cycled or recycled between plants and the atmosphere.

Climate Variations

The meteorological community would simply say that patterns are associated with the Southern Oscillation or El Nino events, as well as other quasi-cyclic phenomena, such as the presence of the local 'mesometeorological' sea breeze or a synoptic presence as, for example, troughs, highs, fronts, tropical cyclones, or, instead, the vagaries of the warm Leeuwin Current. Certainly understanding climate and interpreting events is critical, but dismissal of the regional and local meteorology and physics is not wise. And simply naming a phenomena, be it global, synoptic, or local, tells us little or nothing about it; it is important to have information built upon detail and dissection, common sense, basic physics and mathematics; knowledge based on application of scientific principles (Feynman p 4, 2005). Just as important is to doubt the mantra; of governments, experts and the media. Especially today, with all the information there is a lot of misinformation; the act of doubting is the science that discriminates between the two (Ibid, p 24).

Concern about water supply and the Gngangara mound should consider cycles: for storage and maintenance of the catchment; runoff, drainage and flood risk; for groundwater recharge during heavy rains and wet periods; for the health of wetland ecologies; for evapotranspiration and moisture recycling from woodlands and wetlands; as well as for the redelivery of the local rainfall. An understanding requires the application of the scientific approach, inquiry and doubt; impartial and reasoned critiques need to be generated. This is a key role of science and it is hoped that this paper takes on such an approach, investigating at a regional scale the cyclic nature of long term rainfall data. Perhaps we have peeled away some of the mantura.

Previous European Analysis of Cycles

The consideration of long and medium period global cycles on regional climate and weather is not new (Pettersson 1912 in Carson 1951). Using the features of the Baltic Sea, Pettersson (ibid, p182) speculated that solar and lunar cycles were supporting cycles of 9, 18, and 36 years but also with major extremes at 550AD and 1433AD and perhaps again, around 2400AD.

Western Australia People and Population

Nyoongar experience, knowledge and wisdom worked within a sustainability focused framework with a much smaller population than the present (Berndt, 1979). Though European Australians have been in South West Western Australia for less than 180 years, Nyoongar Indigenous Australians have lived here for perhaps 60,000 years. Water clearly has a main role in sustainability, and in this driest of continents, far drier and far wetter periods have occurred, and some records have been passed on traditionally and been documented (Hassel 1975).

Aboriginal oral culture functions to pass on an accumulation of important knowledge and events from before and during great, grandmother's time (ibid). The oral culture process of passing cultural information from the Elders (who also have deep and clear memories of their childhood) to youngsters (who are able to form deep and clear memories) makes for a robust transfer of knowledge. With built-in cross checking, memory errors may be minimized so that the Nyoongar (and possibly also the ancient Celts) in 3 to 4 generations might bridge perhaps most if not all of 9, 18, 36 and 120 year cyclic patterns.

Closing

The present data implies that effects of global climate change on our regional or local hydrological system may not be as radical as expected. The recognised cycles of natural rainfall that have continued for over 100 years. In the face of global change; we might still reasonably expect this coastal system to continue to provide and maintain the robust and reliable but cyclic rainfall experienced in Perth.

However, the cyclic patterns are longer than memories and there is still a worry about local rainfall changes and a diminishment in the normal rainfall increase as you cross the coastal plain and pass up onto the Darling Scarp, and across the Darling Plateau. Local changes may be influenced by development and removal of local vegetation and wetlands, the formation of heat sinks and loss of natural feedback processes.

We do need to improve our alignment with, and to contribute to global, regional and local sustainability initiatives. In line with Ramsar Wise Use of Wetlands guidelines, we also need to stop natural wetland loss and system disruption, reduce the draining and wasting of water to the ocean and allow the local natural environment—vegetation and ecological niches, trees, the wetlands and waterways—to operate as they should. We need to contribute positively. We cannot simply blame our lack of water on climate change—we have been an irresponsible element and we must in future reduce our water useage and impact.

Messages:

- Cycles in rainfall should not be ignored. In Perth these deterministic components may be as high as 40%.
- Wetlands and woodlands are important components of the landscape and the ecosystems; they are not just evapotranspiration pumps.
- Water balances need to integrate groundwater modeling, surface water modeling, vegetation modeling and atmospheric modeling, to include full feedback systems
- The natural system regularly supplies water. We should not waste water or disable the natural system.

Acknowledgements

The idea for this paper was spawned by Ryan Vogwill (Water Corporation and CALM) who initially supplied the SILO data; later he supplied edited material, criticism, and references. Ian Foster (Department of Agriculture and Food) also supplied data references, critique and many explanations for rainfall patterns. Nonetheless, this paper was generated with the support of Alan Scott and Brian Kowald from the Bureau of meteorology in Perth; Alan Scott also kindly reviewed the paper at the last minute. Special help and knowledge of the SILO site came from Tony Smith of CSIRO, Land and Water. Phil Commander's review of paleoclimate studies in Western Australia allows a connection to work by Karl-Heinz Wyrwoll and Steve Appleyard. Brian Ryan of the CSIRO Division of Atmospheric Physics also has contributed substantially our resolve and acceptance of climate change. Last but not least we recognize that without Ross Lantzke's recovery of the Word files there would be no paper.

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