The Risks and Impacts of Coal Mine Subsidence on Irrigation Areas

Prepared for Cotton Australia
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Summary of Findings

- Some 94% of irrigated lands in the Central Highlands of Queensland are covered by various mining exploration / mining licenses.
- Based on long term experience throughout the world, subsidence is virtually an inevitable impact of underground mining.
- The extent of subsidence varies with type of mining, with bord and pillar likely to slowly create melon hole type landscapes, while longwall mining creates long closed rectangular basins within a few months of mining.
- In both cases the subsidence area extends beyond the physical boundaries of the mined area.
- The depth of the subsidence varies with mining type and local geology. The maximum subsidence under longwall mines is around 65% of the coal seam thickness. Thus a mining a 2m seam will result in a typical maximum of 1.3m subsidence. The initial bord and pillar working, typically removes 30% of the coal, and results in initial depressions of a few centimetres. Second working to increase coal removal to closer to 50% causes partial collapse of the remaining pillars and the subsidence depth eventually approaches that of longwall mining.
- Subsidence from bord and pillar mining is gradual, so there is a need to continually adjust surface activity to allow for its occurrence.
- Subsidence of even 0.5m is predicted to have catastrophic effects on irrigated cotton growing. The key reason is that the cotton fields are laser graded to 1:1000 to 1:1500 slopes, i.e.0.6 to 0.85m fall over an 850m irrigation run. A 0.5m depression across such an irrigation run would make it inoperable. The field could be regraded, however the long subsidence period under bord and pillar systems means that regrading will need to be repeated a number of times. Additionally, there is the practical difficulty of finding the large quantity of suitable fill required.
- Other subsidence impacts on irrigated cotton soils include waterlogging, compaction and irregular ripening of the crop. Salinisation may also be encouraged. All these impacts reduce cotton yield.
- Infrastructure including irrigation supply channels, flood levees, farm dams, farm buildings, cotton processing facilities, roads and tracks are all under threat from mine subsidence.
- Irrigated cotton is largely on black cracking clays (vertosols). These soils are highly prized for irrigated cotton growing and there are very limited opportunities to re-establish irrigated cotton growing elsewhere.
- Yield loss on mine subsidence land is not universal. Rather it occurs when a set of conditions are present. These conditions include:
  - The land surface is relatively flat
  - The soils are clay dominant, especially with cracking clays
  - The site is flood or furrow irrigated
  - The crop is sensitive to waterlogging
  - The crop is grown in summer when warm temperatures will increase soil respiration rate, reducing the time to onset of anoxic conditions

All of the above determinants apply to irrigated cotton growing in the Emerald area.

Both irrigated cotton growing and mining are legitimate activities that contribute significantly to Australia’s wealth. However there is a fundamental incompatibility in landuse. Co-existence on the same parcel of land is not viable. This makes subsurface mining a major threat to the viability of long established irrigated cotton lands.
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This discussion paper is to provide Cotton Australia with a review of evidence concerning the risks and potential impacts of mine subsidence on irrigated cotton.

The use of information and figures from the Mine Subsidence Board (MSB) and Mine Subsidence Engineering Consultants (MSEC) is gratefully acknowledged.

It is time and site specific and must not be used for any other purpose.
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1. INTRODUCTION

The purpose of this discussion paper is to identify the potential risks to the dryland and irrigated cotton industry from subsurface mining.

The paper includes:
- A discussion of underground coal mining methods
- A discussion of irrigated and dryland cotton production, including critical infrastructure such as water supply channels, flood levees, access roads and tracks, harvesting machinery and cotton gins
- A discussion of subsidence including site conditions that determine extent of changes to surface conditions
- A review of studies into subsidence impacts on both irrigated and non-irrigated agriculture
- A discussion of the potential impacts of underground mining on cotton growing in the Emerald Irrigation Area
- Conclusions that provide an assessment of probable and possible impacts and potential responses.
- Recommendations

2. UNDERGROUND COAL MINING METHODS

There are two major types of coal mining currently used in Australia:
1. Open cut
2. Underground mining by either bord and pillar or longwall techniques

2.1 OPEN CUT MINING

Open cut mining is commonly used where the coal seams are relatively close to the surface and the value of the surface lands is relatively low. Open cut mining requires removal of the surface layers (overburden), then drilling, cutting and blasting the seam followed by removal to processing areas. Typically, the overburden is stockpiled and then returned to the pit at mine closure. Usually the topsoil is retained separately and used to cover the disturbed area. However, the volume of the disturbed material exceeds the undisturbed volume, so there is often a 'sugar-loaf' shaped hill left on the site.

Open cut mining is normally more efficient at removal of coal than underground methods. However the economics depend on the land values and the depth to the coal and the costs of rehabilitation. Open cut mines can typically extract 90% of the coal deposit. Open-cut mining currently accounts for 65% of raw coal production in NSW.

2.2 UNDERGROUND MINING

Underground mining requires tunnels to the coal seam. These tunnels are used to convey workers, machinery and extracted coal.

BORD AND PILLAR SYSTEMS

Underground mines used to be largely based on bord and pillar systems. The system is still used today, for example at Ensham Mine Central Queensland.

This system utilises a series of regularly spaced and sized tunnels to remove a proportion of the coal (Bord and Pillar mining, Uni Wollongong website, accessed 15.1.2013). Typically significantly less than 50% of the coal is extracted via the first working. Second working, which involves removal of some pillars, increases the percentage of coal that is extracted, but this also increases the extent of subsidence.
The pillars of coal left between the tunnels are (normally) expected to support the overburden in the medium term. However adequate design requires a good knowledge of the overburden and the layers below the coal seams. Often there is considerable variation in the geology above and below the coal seams, so it is difficult to predict the long term ability of the coal pillars to support the overburden.

Figure 2.1. Cut-a-way view of a bord and pillar mining. The first working removes at least 30% of coal and this is likely to create subsidence of the order of 20mm (copied from: MSB, 1997). Further subsidence depends on the ability of the pillars to support the overburden.

Figure 2.2. Cross section of coal seam and overburden. The initial bord and pillar workings are shown as worked area (Copied from MSB, 1997).
Pillar dimensions are critical to the long-term stability of the overburden. The size of pillars that are sufficient to provide long term stability is dependent on

- the strength and nature of the coal and surrounding strata,
- the height of the pillar,
- discontinuities such as cleats and mining induced fracture planes in the pillar,
- the pillar's width and length,
- the width of the headings defining its boundary and
- the three dimensional stress field existent at the pillar (Bord and Pillar mining, University of Wollongong website, accessed 15.1.2013).

The University of Wollongong website states that in very general terms where headings are driven 6 m wide and not more than 4 m high, pillar centre dimensions of around 50 m x 50 m are usually stable to depths of 600 m.

In practice the intensity of the support varies from almost nothing in the case of shallow mines having hard conglomerate or massive sandstone roof; to closely spaced steel cross supports or arches supplemented with bolts where the workings are deep and the roof is weak laminite, mudstone or coal.

Second workings of bord and pillar systems involve partial or almost complete removal of the pillars. Figure 2.3 shows a cut-a-way of the pillar removal.

Figure 2.3. Cut-a-way view of a second working where the pillars are being removed (copied from MSB, 1997).

The anticipated impact on subsidence is shown in figure 2.4. An important feature of subsidence following partial removal is that it can be controlled via leaving some pillars in place. This results in ‘humps’ and hollows’ above the mined area. The importance of the undulations depends on the topography and uses of the overlying land surface.

The extent and severity of the undulations can be approximated by modelling provided there is sufficient information regarding the site physical conditions and its geology (Sroka et al, 2011, and MSEC, 2011 reports).
The rate of formation of the humps and hollows is a function of the time it takes for the pillars to collapse. In partially collapsed systems this can take years or even decades to stabilise (Sgambat, et al, 1980). The extent and impacts of delayed subsidence are difficult to predict (Bell, et al, 2000).

![Image of subsidence zones](image)

Figure 2.4. Extent of subsidence is dependent on the extent of collapse of the pillars between panels (Copied from MSB, 1997).

**LONGWALL SYSTEMS**

Longwall systems aim to extract as much coal as can be safely and economically removed. Typically the system involves removal of 80 to 90% of the available resource. MSEC (2007) provides a good general discussion of longwall mining. According to MSEC, longwall panels are normally 150 to 300m wide, 1000 to 3500m long, and 2 to 5m thick. Figure 2.5 shows a typical operation.
RISKS AND IMPACTS OF COAL MINE SUBSIDENCE ON IRRIGATION AREAS

Figure 2.5. A cut-a-way of a long wall operation showing a completely removed panel, a remnant pillar between the panels and a partly removed panel (Copied from MSB, 1997).

The system is designed to collapse behind the advancing longwall shearer and the conveyor as figure 2.6 shows. An important feature is that unlike the bord and panel mining system, the collapse occurs relatively soon after the creation of a void. Booth and Spande (1992) reported that the bulk of the subsidence occurred within 10 weeks of mining. Another 0 to 10% subsidence occurs over the following year (Whittaker and Reddish, 1989). The extent of subsidence depends on the thickness of the seam being mined, the thickness of the overburden and the local geology.

According to the MSB (1997) the indicative subsidence in NSW is approximately 65% of the seam thickness. So mining a 2m thick seam will result in a 1.3m subsidence. This ratio is consistent with the records of Hinchcliffe (2003) who reported a 1.8 to 1.9m subsidence under 2 to 3.5m thick seams in the Lilyvale area.

Figure 2.6. Cross section of typical longwall face (Copied from MSEC, 2007).

Figure 2.6 is copied from a review paper by MSEC (2007). It shows the development of cracks and eventual collapse of the overburden creating goaf\(^1\). Expansion cracking occurs on the upper portion of the subsidence zone. Compression occurs on the lower slope of the subsidence. Both expansion and compression have marked impacts on soil condition and hydrology.

2.3 Subsidence characteristics

One principal surface impact of underground coal mining is subsidence (lowering of the surface above areas that are mined (see Booth et al., 2000, and Holla and Barclay, 2000). The total subsidence of a surface point consists of two components, active and residual. Active subsidence, which forms 90 to 95% of the total subsidence in most cases, follows the advance of the working face and usually occurs immediately. Residual subsidence is time-dependent and is due to readjustment and compaction within the goaf (Holla and Barclay 2000).

Trough-shaped subsidence profiles associated with longwall mining develop tilt between adjacent points that have subsided to different extents. Maximum ground tilts are developed

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\(^1\) Goaf is the collapsed overburden that fills the void created by the mining. Figure 2.6 shows an example.
above the edges of the area of extraction and may be cumulative if more than one seam is worked up to a common boundary.

Importantly, the surface area affected by ground movement is greater than the area worked in the seam (Bell et al. 2000).

In the NSW Southern Coalfield, horizontal displacements can extend for more than one kilometre from mine workings (and in extreme cases in excess of three km) (ACARP 2002, 2003), although at these distances, the horizontal movements have little associated tilt or strain.

Subsidence at a surface point is due not only to mining in the panel directly below the point, but also to mining in the adjacent panels. It is not uncommon for mining in each panel to take a year or so, and therefore a point on the surface may continue to experience residual subsidence for several years (Holla and Barclay 2000).

According to Rio Tinto (2006), the estimated maximum subsidence at the Kestrel mine near Emerald is 2m. The indicative dimensions are shown below.

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**Figure 2.7. Estimated subsidence under a 250m wide longwall block for the Kestrel Mine near Emerald (Copied from Rio Tinto, 2006)**

Figure 2.7 also shows that the subsidence extends beyond the width of the longwall block. At Kestrel Mine, the subsidence was estimated to extend 40 to 90m from the edge of the longwall block (Rio Tinto, 2006). The distance is a function of extraction depth and the angle of draw. The angle of draw is a function of the overburden conditions, and can range from zero to 35°.

The subsidence creates strains in the surface soil. The strain is measured as change (mm)/original distance (m), which is mm/m. The strains can be compressive or expansive (tensile) strains, depending on local conditions. Compression will increase soil bulk density thereby reducing soil internal drainage and aeration. Expansion will create cracks, increasing infiltration loss through the soil. If expansion occurs during the growing season it can damage the cotton root system by pulling the roots apart and by exposing the roots to dry air.

Obviously the extent and severity of subsidence within a mined area will depend on local conditions, including the proportion of the seam that is mined.

The impacts of the subsidence depth and other subsidence parameters are highly dependent on the activities and values placed on the land surface. The activities specifically associated with the cotton industry are discussed below. However the impacts on other activities including road
transport, urban development, dryland cropping, floodwater distribution and incidence of waterlogging, and the retention of values such as flowing streams and water supply security should also be considered.

### 2.3 THE INEVITABILITY OF SUBSIDENCE FROM UNDERGROUND MINING

Blodgett and Kuipers (2002) provide a comprehensive overview of mine subsidence and its hydrological impacts. They cited mining industry handbooks such as the ones below to demonstrate the inevitability of mine subsidence.

“Subsidence is an inevitable consequence of underground mining – it may be small and localized or extend over large areas, it may be immediate or delayed for many years” (SME, 1992). Fejes states that subsidence is “a natural result of underground mining” and goes on to write that, “When a void is created nature will eventually seek the most stable geologic configuration, which is a collapse of the void and consolidation of the overburden material” (see Mining Environmental Handbook, 1997).

The NSW Southern Coalfields Review concluded that with few exceptions, at depths of cover greater than about 200 m, coal cannot be mined economically by any mining method without causing some degree of surface subsidence. If mining of hard coking coal in the Southern Coalfield is to continue, then a certain level of subsidence impact must be accepted as a necessary outcome of that mining (NSW Government, 2008).

Hinchcliffe (2003) reported on the impacts of longwall mine subsidence from two mines in the Emerald area where the seam thickness varied from 2 to 3.5m. There was subsidence under both panel and pillar areas. The subsidence was 1.8 to 1.9m in the centre of the panel areas and 0.4 to 0.5m in the pillar areas.

The issue is not that mine subsidence will occur, overwhelming evidence from throughout the world shows that it does (e.g. SME, 2011), irrespective of type of underground mining (Whittaker and Reddish 1989), rather the issue is to what extent will the subsidence impact on irrigated cotton growing?
3. COTTON FARMING

Cotton has been grown in Australia since the arrival of the First Fleet. The first cotton exports occurred in the 1830s. Cotton production has expanded markedly in the past fifty years from 9,000 bales in the 1960s to an average of 2.2 million bales since 1992. The total value of the Australian cotton crop in 2010/11 was $2.9 billion.

The Australian cotton crop was produced on 579,000 ha in 2010/2011. Approximately 1/3 of the cotton cropping area is in Queensland with the remaining 2/3 being in NSW (Cotton Australia web site accessed 13.1.2013).

3.1 CONTRIBUTION OF THE COTTON INDUSTRY TO THE LOCAL ECONOMY

Irrigated cotton growing makes a major contribution to its local communities. Johnson (1998) estimated that for every $1 of production created by the irrigation sector, which includes farming, processing, transport, extension and other services, a further $5 of output benefit is created in local communities. Additionally, for every 1 person employed in the irrigation sector, a further 3.7 persons will be directly employed in support or infrastructure jobs elsewhere (Johnson 1998).

3.2 COTTON AS A HIGH INPUT HIGH RETURN ENTERPRISE

Cotton is a summer growing plant, typically planted in September-October and harvested in autumn. ABRE predictions indicate some 419,000 ha of the 2012-13 cotton crop is irrigated. Another 23,000 hectares is grown under dryland conditions.

Cotton irrigation typically consists of furrow irrigation down laser graded fields. The grading is expensive and precise, providing even 1 in 1000 to 1 in 2000 slopes over lengths of up to 1000m.

Figure 3.1. Precision agriculture techniques are widely used in irrigated cotton fields to identify ridges and depressions.
In the example above, there are areas where the grade is negative. These are likely to become waterlogged. Cotton yield would be depressed in these areas. Trafficability would be greatly impeded and this would make harvest difficult.

The information generated is used in:
- Prioritising areas for remedial earthworks.
- Designing surface drainage to improve trafficability.
- Designing farm layouts to manage water flow and erosion (From Cotton Catchment Communities CRC, 2011).

Figure 3.2. An intensive electromagnetic (EM) survey is used to identify drainage and other issues within a field (Source: Cotton Catchment Communities CRC, 2012).

Figure 3.3. Yield from individual portions of the field shown in figure 3.2.
A comparison of figures 3.2 and 3.4 shows the type of precision agriculture being used to identify the reasons for yield variation, and thereby optimise economic returns from irrigated cotton. Sags in the field can be readily identified with GIS equipment and the results related to variation in yield. This is then addressed by re-grading the field. Normally regrading involves adjusting local height variations of 10 to 100mm. This is an order of magnitude less than the several metres deep depressions that can result from mine subsidence.

Irrigated cotton is a high input activity, using precision agriculture to optimise economic returns. Mine subsidence will create irregular grades within irrigation ‘runs’. The irregular grades, creating negative slopes and depressed areas can have catastrophic impacts on economic returns.

A significant proportion of the Australian cotton crop is grown on agricultural lands overlying coal seams that are currently being assessed for mining. Mining these seams is likely to impact severely, especially on irrigated cotton production. The next sections examine (in detail) the potential impacts of coal mining on cotton production.
4. RISKS AND POTENTIAL IMPACTS OF UNDERGROUND MINING ON THE COTTON INDUSTRY

According to SME Mining Engineering Handbook (2011) subsidence impacts agricultural lands via processes such as formation of surface fissures, change in ground slope, changes to surface drainage, disruption of ground water hydrology, deterioration of surface and ground water quality, and occurrence of subsidence areas. Additionally compression and expansion strains can impact on soil physical conditions such as bulk density and oxygen diffusion.

The Dept Interior, Bureau of Land Management (1983) recognised that subsidence following coal mining could disrupt surface and groundwater distribution patterns and dislocate infrastructure including roads and pipelines.

Hansen Baily (2009) stated that ‘Cropping land associated with mining development is typically downgraded post-mining’. Obviously the extent of damage is site specific and depends crop type, climate and on the relative impacts of mining on the cropping land attributes.

The Queensland Government (1995) provided an early report on effects of mine subsidence on agricultural and rural land. According to this government report:

Subsidence effects that influence agricultural activities can be listed as follows.
(1) Above ground structures and installations on farms may be structurally damaged or their performance impaired by strain and tilt due to subsidence.
(2) Drainage flows may be stopped due to change of surface level.
(3) Stream flow may be interrupted.
(4) Water extraction from wells may be impaired or prevented by damage to a well or bore and by interruption of the subsurface aquifers.
(5) Ponds may be created that are not self-draining, destroying crops and pasture.
(6) Irrigated land that has been accurately levelled for even and precise irrigation may be significantly altered.
(7) Large tension cracks on the surface may be hazardous to persons and animals. Tilling or ploughing land over cracks may be difficult or impossible.
(8) Low lying land at the edges of natural or manmade water storages may be flooded.
(9) Roads, pipelines, power transmission lines, sewerage works and like structures may be damaged.
(10) It may not be possible to harvest some of a crop.
(11) Water and tailings dams may be damaged.

It is obvious that the Queensland government had significant concerns almost 20 years ago.

In July 2005 the ‘Alteration of habitat following subsidence due to longwall mining’ was listed by the independent NSW Scientific Committee as a key threatening process under Schedule 3 of the NSW Threatened Species Conservation Act 1995.

The NSW Scientific Committee recognised that subsidence due to longwall mining is the cause of habitat alteration, including cracks beneath a stream or other water bodies, and that subsidence may lead to “a temporary or permanent loss of water flows and could cause permanent changes to riparian community structure and composition”. The Committee also noted that, “Species and ecological communities that depend on aquatic and semi-aquatic habitats are particularly susceptible to the impacts of subsidence. Subsidence can cause a decrease in water quality such as reduced oxygen availability, encouraging bacterial growth, smothering native plants and animals. Subsidence can also increase the amount of iron oxides in the water which directly affects native plants and animals.

A summary of impacts that negatively impact agricultural activities listed in the referenced literature includes:
RISKS AND IMPACTS OF COAL MINE SUBSIDENCE ON IRRIGATION AREAS

(1) Above ground structures and installations on farms may be structurally damaged or their performance impaired by strain and tilt due to subsidence.
(2) Local drainage flows may be stopped due to change of surface level.
(3) Stream flow may be interrupted.
(4) Water extraction from wells may be impaired or prevented by damage to a well or bore and by interruption of the subsurface aquifers.
(5) Ponds may be created that are not self-draining, waterlogging crops and pasture and thereby reducing yield.
(6) Irrigated fields on individual farms that have been accurately levelled for even and precise irrigation may be significantly altered, destroying the irrigation system.
(7) Severe subsidence and cracking could make gravity fed irrigation schemes such as the one in the Emerald Irrigation Area non-functional. It could even lead to abandonment of individual channels.
(8) Large tension cracks on the surface may be hazardous to persons and animals. Tilling or ploughing land over cracks may be difficult or impossible.
(9) Low lying land at the edges of natural or manmade water storages may be flooded.
(10) Roads, access tracks, pipelines, power transmission lines, sewerage works and like structures may be damaged by the strains from tilting and subsidence.
(11) It may not be possible to harvest some of a crop due to localised waterlogging in rain growing fields.
(12) Water storage and tailings dams may be damaged.

Not all the potential impacts listed above are applicable to irrigated cotton growing. The list below identifies the potential impacts on underground mining on the irrigated cotton industry.

- Mine subsidence causing disruption to irrigation channels and supply ditches.
- Mine subsidence causing uneven tracks and cracking of roads.
- Mine subsidence destroying the integrity of farm dam walls and floors.
- Mine subsidence causing structural damage to cotton processing infrastructure.
- Mine subsidence disrupting the surface of irrigation bays, preventing even distribution of water, and causing moisture stress in hump areas and waterlogging in subsidence areas.
- Under severe subsidence, e.g. more than 0.5m the water would lie in the depressions, drowning parts of the crop.
- The humps and hollowing in non-irrigated lands can result in differences in water supply to adjacent portions of the fields. This can lead to under or oversupply of moisture depending on the season. The moisture supply variation can result in variation in production and in maturity time, making it difficult to harvest at the optimal time.
- Mine subsidence causing differential cracking and compression of surface soils, resulting in changes in infiltration patterns and bulk densities.
- Mining impacts on groundwater supply and quality.

These impacts are discussed below.
5. IMPACTS ON IRRIGATION SUPPLY SYSTEMS

Bulk water supplies to Queensland cotton crops are delivered largely via SunWater. SunWater is a bulk water infrastructure developer and manager supplying approximately 40% of all water used commercially in Queensland. SunWater’s network of water supply infrastructure supports mining, power generation, industry, urban development and irrigated agriculture throughout Queensland (SunWater website accessed 17.1.2013).

Mine induced disturbance to the ground surface can have a range of impacts on water supply systems. These include:

- Subsidence zones that lie across an established supply channel. These can result in water escape from the channel. The bank erosion from water overtopping the banks will cause bank lowering via erosion. The lower bank will result in more water being lost. Additionally, the subsidence zone will remain wet and difficult to clean out when maintenance is required.

- Subsidence which creates negative grades along the channel. These will require increased bank heights in order to maintain flow and delivery, and to prevent escape of water from subsidence areas.

- Expansion areas on the upper edges of the subsidence. Expansion joints can extend to the ground surface, creating significant opportunities for deep penetration of water. This will represent a loss of water from irrigation channels. The extent of loss is a function of the curvative of the subsidence profile, the availability of the water, the soil type, and the increase in porosity/hydraulic conductivity between the ground surface and the voids within the subsidence zone. The expansion areas can also have increased movement of water to subsurface layers, increasing risk of salinisation.

Blodgett and Kuipers, (2002) reviewed hydrological impacts of underground mining in the USA. They cited numerous examples of changes in hydrology due to mine subsidence (e.g. SME Mining Engineering Handbook, 2011).

![Figure 5.1. Effect of mine subsidence on a field in N Carolina (copied from website).](image-url)

There would be catastrophic consequences if subsidence such as the one in figure 5.1 occurred across a water supply channel.

Hinchcliffe (2003) noted subsidence varied between 0.4 and 1.9m under longwall mines depending on the location of the panels and pillars. This irregularity would create major disruption to irrigation channels, especially across relatively flat landscapes (Darmody et al 1988, Hinchcliffe, 2003). Hinchcliffe also noted that ‘significant changes did occur to creek lines’.
6. MINE SUBSIDENCE CAUSING DAMAGE TO ROADS AND TRACKS

Damage to roads and tracks can be significant, especially if mining is actually occurring under them (See for example MSEC, 2011). A major concern is trafficability on unsealed roads. These local roads provide the only access to many cotton farms. They are on relatively flat grades and are often constructed using local, reactive soils.

Cotton growing soils typically have low strength when wet (NSW Dept Primary Industries, 1998). Creation of closed troughs with a typical depth of 50 to 60% of the coal seam thickness on the flat landscape means that rainwater cannot drain. The softness of the soil means that rutting can be severe, even with occasional, necessary traffic when the road/track is flooded. The soft condition and deep ruts can make the road impassable when wet and dangerous to drive on when dry.

Agronomic operations and even harvesting can be significantly delayed. This exposes the crop to more risk of rain damage.

7. MINE SUBSIDENCE CAUSING DAMAGE TO COTTON INDUSTRY INFRASTRUCTURE

Cotton industry buildings such as gins and warehouses as well as farm sheds and homes will be subject to risk of subsidence damage if there is any underground mining either directly under or within the angle of draw of subsidence areas (MSB, 1997). This becomes a complex problem if the subsidence is gradual as is expected from bord and pillar systems.

8. MINE SUBSIDENCE DISRUPTING THE SURFACE OF IRRIGATION BAYS

The cotton fields are typically laser graded to create a simple slope with no hollows or humps. This precision is essential as both waterlogging and moisture stress can depress cotton yield. The grades are typically between 1:1000 and 1:1500. Recommended maximum field length is 800 m. The typical change in elevation between the top and the bottom of the irrigation run would therefore be 0.5 to 0.8m.

A 0.5 to 2m ‘sag’ due to mine subsidence across an irrigation field would cause major disruption to water distribution along the furrow. The uneven watering would make the irrigation system inoperable as well as lead to significant yield loss. See http://www.cottoncrc.org.au/content/Industry/Publications/Water/WATERpak.aspx

According to the Cotton Industry’s Best Management Practice, landholders should retain the first 25mm of field rain runoff plus all tailwater on farm via the use of reticulated tailwater storages. Subsidence between the end of the irrigation area and the tailwater storage would make this collection system inoperable. This would increase risk of soil borne and water borne contaminants (farm inputs) reaching streams. (Note area is a Great Barrier Reef Catchment)

Figure 8.1 shows a typical furrow irrigated field.
Figure 8.1. Irrigated cotton field near Emerald (photo by CQCUSKELLY). The fields are laser graded to enable an even rate of water advancement down the field and to prevent waterlogging in ‘sags’. (Source: WATERpak Ch. 2.5)

Figure 8.2. Cotton is extremely sensitive to even temporary waterlogging following irrigation. Relatively minor sags in this field have resulted in waterlogging and crop yellowing. The sags are typically 5 to 50 mm deep. This is more than 10 times less than that experienced from mine subsidence (Hinchcliffe, 2003).
Figures 8.3 and 8.4 show examples of mine subsidence impacts. These impacts would make laser graded irrigation fields inoperable.

The figures also show considerable variation in subsidence size and depth. This reflects the type of mining, the depth of the mine activity and the seam thickness. Marschalko et al (2012) reported that subsidence of up to 11 m occurred over a 25 year period in the Ostrava–Karvina Coal District (Czech Republic). Subsidence of 11m is not expected to occur in the Emerald area. However in relatively flat lands, such as those used to grow furrow irrigated cotton, 0.5m of subsidence will create agronomically, and therefore economically, significant changes in the irrigation system.

Figure 8.3. Waterlogging in a field affected by mine subsidence (Source: Uni Indiana, Indiana Geological Survey web site accessed 18.1.2013). Web site accessed 18.1.2013). Note that the waterlogging is occurring in basins less than 0.5m deep.
According to the Central Queensland Golden Triangle website (accessed 15.1.2013), ‘the subsidence occurring as a result of underground mining will significantly alter surface topography, and drainage of runoff. Farmers have made significant investments in drainage works, including contour banks, waterways, levee banks, laser and other levelling works, to help reduce erosion in their paddocks, and to facilitate the efficient disposal of runoff or overland flow water. This infrastructure will be rendered useless if substantial subsidence changes surface topography and surface drainage patterns. Repairing such damage would be very expensive and unviable for family farms.

A similar impact to this occurred in the 1990s on “Gordon Downs” a non-irrigated property on undulating lands near Capella following subsidence from underground mining.

In this case, the existing contour bank system had to be totally removed, and a new one designed and re-built following subsidence during and after the long-wall mining operation.

Further, the changed surface topography rendered subsequent farming operations unworkable due to the variable topography and huge contour banks that were required thereafter’.
9. MINE SUBSIDENCE CAUSING DIFFERENTIAL CRACKING AND COMPRESSION OF SURFACE SOILS

Expansion zones are likely to be created on the upper 'lip' of a subsidence zone as figure 2.6 shows. The expansion cracks provide preferential flow paths for water. This can disrupt distribution within irrigation systems. Cracks of more than 20mm width can break root systems, increasing plant moisture stress.

Compression is likely to occur in the lower portion of the subsidence lip. The impact of this compression and expansion will depend on local conditions. The results of Hu et al (1987) are consistent with this: They found that both bulk density and soils water content increased between the edge of the subsidence and the centre of the subsidence trough. The compression means that the soil bulk density has increased. This reduces the rate of diffusion of air through the soils. Cotton is particularly susceptible to waterlogging and consequent reduction in air diffusion (NSW Dept Primary industries, 1998).

In expansive or reactive soils the compression resulting from subsidence can eventually be reversed provided it is not more than a few centimetres (NSW Dept Primary Industries, 1998). Many irrigated cotton crops are planted into these soils. These soils are largely reliant on the cracks for internal drainage. They have very rapid infiltration when dry and cracked, but once the cracks close the infiltration capacity approaches zero. Compression from mine subsidence can markedly reduce infiltration capacity of soils around the lower portion of land surrounding the subsidence zone. Thus there is reduced infiltration capacity within the lower portion of the basin resulting from mine subsidence.

In effect, the subsidence zone itself acts as a closed basin with minimal opportunity for surface drainage.

Dryland cotton is also grown on non-reactive soils. Compression of these soils is likely to be semi-permanent.

Compression impacts are likely to be greatest if the compression occurs when the soil is wet. A slow subsidence, anticipated under bord and pillar mining, is likely to be exposed to wet weather during the subsidence period. The reason for this is the irregular drainage means that portions of the crop will mature at different times. Consequently, the harvest will need to be delayed until the least mature portion ripens. This means that the most mature portions are left exposed to the risk of wet weather damage for longer periods.
10. **MINE SUBSIDENCE CAUSING DIFFERENTIAL SOIL WATER CONDITIONS**

Blodgett and Kuipers, (2002) cited regulations addressing the impacts of underground mining on agricultural production going back 5 centuries: ‘In 1556 Georgius Agricola noted in De Re Metallica…that the Italians had forbidden any mining in or around the extensive vineyards and fields of the prime agricultural regions because of the negative impacts of subsidence and degraded water quality caused by mining (Agricola, 1950).’

The subsidence zone itself acts as a closed basin with minimal opportunity for surface drainage as figures 2.6, 2.7, 5.1, 8.2 and 8.3 suggest. This would be especially important in relatively flat lands (Darmody, et al, 1988). Under dryland agriculture these closed depressions can retain rainfall runoff for long periods during (relatively rare) heavy, prolonged rainfall events. In northern NSW and QLD these are most likely to occur during later summer when the cotton crop is susceptible to waterlogging.

Chinese researchers found that semi-permanent ponds could develop in subsidence depressions. Obviously the extent, depth and duration of the flooding are dependent on local conditions. The shape of the ponds/depressions reflects the type of mining. Figure 8.2 shows an elongated trough that is likely under a longwall system. Figure 5.1 shows a more rounded system that could occur overlying a bord and pillar mine.

In Shendong coal mining area, coal mining had no significant change in surface moisture. Rather, the main impact of mining was to cause the water table to fall from 35 to 43m.

The soil type is important in determined response to mining. Soils which expand when wet, and shrink and crack when dry (often referred to as expansive or reactive soils) have relatively poor internal drainage. The low saturated hydraulic conductivity of the cracking soils means that they will remain wet and untrafficable for long periods if there is no surface drainage. The vertosols in the Emerald cotton growing area are predominantly reactive soils.

The effect of flooding/ waterlogging is dependent on the vegetation type and its growth stage. Flooding can be especially damaging to cotton seedlings. Flooding can also reduce maize growth (Lizaso et al, 2001). Melhuish et al (1991) correlated reduction in wheat yield with increased flood duration. However it is noted that flooding is less likely to be an issue for winter growing crops such as wheat as the cotton growing areas of Queensland and northern NSW have low rainfall in winter. Wheat crops in the area rely on stored soil moisture for growth.

Guither (1986) reported a 40% reduction in maize yield from subsided lands compared with non-subsidied lands. The difference appears largely due to waterlogging on subsided lands. This indicates subsidence can be an issue even under dryland conditions.

The results suggest that differential soil water content is likely to occur in subsidence areas. The extent will depend on the degree of subsidence and the ‘flatness’ of the landscape. Short term changes in moisture content will result from rainfall, irrigation, deep percolation and vegetative water use.

In the relatively flat areas used for irrigated cotton growing, subsidence of even 0.2 to 0.5m is likely to result in significant yield loss due to waterlogging.

Cotton is especially sensitive to waterlogging: The figure below is from Bange et al (2012). They used a threshold of less than 10% air filled porosity (< 0.1 cm$^3$ cm$^{-3}$) to demark waterlogging.

It is obvious that increased duration of waterlogging results in lower cotton yield.
Figure 10.1 Relationship between duration of waterlogging and cotton lint yield (Bange et al. 2012).

Hodgson and Chan (1982) showed that increasing furrow irrigation period from 4 to 16 hrs reduced cotton yield by 8%. Note that this experiment involved furrow irrigation. The effect of flood duration is likely to be more severe as the entire soil surface is covered with water. A 0.5m sag within an irrigation bay would render the system inoperable.
11. MINING IMPACTS ON GROUNDWATER SUPPLY AND QUALITY

The impacts of mining on groundwater quality and quantity have been subject to major investigations in many coal mining parts of the world.

In China, Yang, et al (2008) concluded that subsidence and the cracks formed in the coal area lead to reduction of agricultural output. They also resulted in cease-to-flow condition in local streams while increasing the depth to the water table in other areas. However little data was presented to support these assertions.

Bian et al (2009) reported that there was no significant change in surface moisture. The main impact of mining was to cause the water table to fall from 35 to 43m below the land surface.

Smith, (2009.) cited evidence of Timms and Acworth (2006) that, based on the research that had been carried out in the past 10 years, they believe that coal mining on the Liverpool Plains will impact on the groundwater system used for irrigation, stock and domestic use if mining is carried out beneath the flat-lying plains. They noted that management strategies on the Liverpool Plains are currently addressing the adverse impacts that irrigation development has had on the groundwater system. If coal mining is to proceed, the additional impacts on groundwater recharge, groundwater levels and water quality must be considered. Additional impacts can include:

- Change in aquifer recharge rates
- Interception and disruption to the integrity of the aquifer, and
- Mixing of saline and non-saline groundwaters, and
- Pumpout of saline waters-subsequent use of this water for dust suppression can salinise the surface soil.

Timms and Acworth (2006) note that the age of the groundwater in the Namoi Valley is of the order of tens of thousands of years. In parts of the region high levels of extraction have resulted in the reversal of the natural groundwater flow, and the result is that current pumping may effectively be mining the aquifer. Falling groundwater levels are clearly seen at some sites. (Though these are not mined as yet). Additionally Smith (2009) was referring to potential impacts from open cut rather than underground mines.

Vermeulen and Usher (2006) reported on net influx of water to various types of mines. The percentage influx to be expected for the various mining methods is shown below:

- Shallow bord and pillar: 5–10% of the rainfall infiltrates to the abandoned mine
- Deep bord and pillar with no subsidence: 3–4 % of the rainfall
- Stoping\(^2\): 5–12% of the rainfall
- Longwall: 6–15% of the rainfall
- Rehabilitated open cut: 14–20% of the rainfall.

These results suggest the open cut has the highest rainfall percolation, with longwall next. Both these types of mining are expected to have extensive subsidence areas on the surface.

The relevance of mine subsidence to groundwater supply and the cotton industry is dependent on the extent to which cotton relies on groundwater for irrigation. This varies markedly with irrigation area.

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\(^2\) Stoping is the removal of the wanted material from an underground mine leaving behind an open space known as a stope.
12. RISKS OF MINING IMPACTS ON COTTON GROWING NEAR EMERALD

12.1 Agricultural suitability of Emerald Soils

There have been a number of reports characterising the value of the agricultural lands in the Emerald Area. These are discussed below.

Soil survey of the Emerald irrigation area left bank of the Nogoa River.

Agricultural suitability of Emerald soils was examined in the Soil survey of the Emerald irrigation area left bank of the Nogoa River. The survey was at 1:25 000 scale and covered 16 000 ha on the left bank of the Nogoa River. The report was prepared in preparation for subdivision of land into irrigation farms, each being a minimum of 200 ha at the commencement of the Emerald Irrigation Scheme.

Land resource attributes examined for the soil survey included: landform, slope, soils, lithology, land degradation, cleared land, vegetation and land use.

Land resources of the Emerald irrigation area right bank of the Nogoa River.

The report, Land resources of the right bank of the Emerald Irrigation Area outlines a soil survey (1:25 000) and recommended land uses.

The recommended land uses are agricultural production areas, pasture research areas, forestry production areas, irrigation implementation, urban development, waste disposal, highway planning, mine site rehabilitation, engineering uses, management of small catchments, shire planning (agricultural areas).

Land resource attributes examined for the soil survey include landform, slope, soils, lithology, land degradation, cleared land, vegetation and land use. The soil survey generated the report, digital data and one map. An obvious conclusion from the above studies is that irrigated cotton growing requires a relatively specialized set of climate, soil and landform conditions. These are found in a few places in Australia. The Emerald Irrigation Area is an especially good example of lands suited for cotton growing.

Appendix A of the Guidelines for Land and Water Management Plans. Fitzroy Basin. (July 2005 Reprinted July 2007 with updates to section 2.1) identifies the risk situations where irrigated development is not permitted, unsuitable or a minimum standard is required. The effect of the Guidelines is also to exclude many areas in the Emerald Region from irrigated cotton growing. Examples include:

- No clearing and development within the following distances of watercourses: 200 m either side of the high bank of rivers, 100m either side of the high bank of creeks and 50 m either side of the high bank of gullies.
- Only those soils that are suitable for irrigation should be developed. Soils which are unsuitable or have high inherent risk include:
  - Thin surface texture contrast soils (less than 25 cm topsoil) with ‘tough’ clay surface and bleached sub-surface layer.
  - Cracking clays with any of the following characteristics:
    - a high number of melon-holes
    - a very coarsely structured soil surface

3 Development of melon hole (Gilgai) landscape is a characteristic effect of mine subsidence following pillar and bord mining. Based on NRW (2007) such conditions would render the soil ‘high risk’.
RISKS AND IMPACTS OF COAL MINE SUBSIDENCE ON IRRIGATION AREAS

- soil surface crusts
- high sodium near soil surface.
- Landscapes where salinisation is evident on lower slopes or adjacent lands.

Soils unsuitable for irrigation include black, self-mulching clay soils cracking clay soil (3Vex) on undulating plains and rises on old transported sediments, and brown or grey sodic texture contrast soil (4SOx) on undulating plains and rises over tertiary rocks.

This indicates undulating black soils would be unsuitable for irrigated cotton. These soils form the majority of irrigated cotton growing soils to the NW of Emerald. According to the Fitzroy Basin Land and Water Management Plan (NRW, 2007), they are at risk of becoming ‘unsuitable’ for irrigation because of the undulations that will develop from underground mining.

The Guidelines highlight the value and scarcity of suitable cotton growing areas.

Loch and Rolfe (2000), commented on the fact that cotton crops require deep cracking clays for water retention. The combination of these soils and ability to supply irrigation is a relatively scarce combination. Consequently, the lands near Emerald are highly valued by the Cotton Industry.

The Land and Water Management Plan (NRMW, 2006) emphasises the scarcity of suitable lands for irrigated cotton. That is, it is not simply a matter of moving the irrigation industry to another site in order to allow mining. The suitable land is already being used.

The land is currently laser graded and furrow or flood irrigated. The clay dominant soils mean that alternative irrigation systems such as centre pivot could be bogged. Additionally centre pivot systems are designed to deliver relatively small application rates per cycle. Applying say 10 to 12 mm onto a cracking clay soil typical of the cotton growing areas would simply cause the surface cracks to close up, greatly inhibiting further water entry. Additionally the peak evapotranspiration demand in Emerald is around 15mm per day. Centre pivot systems maximum delivery is typically 12mm per day.

### 12.2 PROPORTION OF IRRIGATION LANDS INTERSECTED BY MINING

Table 12.1 shows the proportion of intersection of the mining industry and the irrigation lands. Irrigated lands cover only 1.2% of the Central Highlands. Yet, total EPC/EPM/EPP (application & granted) and irrigated land use intersection covers 94% of the irrigated land area. Various types of mining licenses; total ML/MDL/PL (Application & Granted) and Irrigated Land Use Intersection cover some 28% of the irrigation area.

These government derived statistics show the extremely high proportion of irrigated lands under ‘threat’ from mining activity.

An additional issue is that even in the exploration phase mining activity poses risks to agriculture: biosecurity is a major issue, especially for high input crops such as irrigated cotton. Landholders are very aware of dangers from pests, diseases and weeds being conveyed on vehicles that move between properties. There is an obvious need for strict decontamination requirements for mining vehicles entering farmlands.
### Table 12.1: Intersection of Irrigated Land Use and Resource Industry Activity (Source Central highlands Cotton Growers & Irrigators Association and Dawson Valley Cotton Growers Association (2012))

<table>
<thead>
<tr>
<th>Land Disturbance (From QRC Flyer 26/9/12)</th>
<th>Banana</th>
<th>Central Highlands</th>
<th>Gladstone</th>
<th>Rockhampton</th>
<th>All Five LGAs of Central</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>6000 ha</td>
<td>34,300 ha</td>
<td>6,000 ha</td>
<td>5,300 ha</td>
<td>Not supplied</td>
</tr>
<tr>
<td></td>
<td>0.2% of</td>
<td>0.6% of</td>
<td>0.2% of</td>
<td>0.3% of</td>
<td></td>
</tr>
</tbody>
</table>

| *Total EPC/EPM/EPP (Application & Granted) | 2,557,378 ha | 5,128,274 ha | 467,447 ha | 1,189,556 ha | 9,381,659 ha |
|                                           | 89.57% of area | 85.71% of area | 44.96% of area | 65.5% of area | 79.96% of area |

| *Total ML/MDL/PL (Application & Granted) | 416,762 ha | 693,192 ha | 60,797 ha | 76,937 ha | 1,247,689 ha |
|                                         | 14.6% of area | 11.59% of area | 5.85% of area | 4.24% of area | 10.63% of area |

| Irrigated Land Use (Irrigated: cropping, perennial horticulture, seasonal horticulture) | 43,498 ha | 71,527 ha | 655.5 ha | 6,908 ha | 122,588 ha |
|                                                                                        | 1.52% of area | 1.2% of area | 0.06% of area | 0.38% of area | 1.04% of area |

| *Total EPC/EPM/EPP (Application & Granted) and Irrigated Land Use intersection | 38,126 ha | 67,083 ha | 435 ha | 3582 ha | 109,226 ha |
|                                                                                 | 1.34% of total land area | 1.12% of total land area | 0.04% of total land area | 0.2% of total land area | 0.93% of total land area |
|                                                                                 | 87.65% of irrigated land area | 93.79% of irrigated land area | 66.3% of irrigated land area | 51.86% of irrigated land area | 89.1% of irrigated land area |

| *Total ML/MDL/PL (Application & Granted) and Irrigated Land Use intersection | 2283 ha | 20,211 ha | 291 ha | 246 ha | 23,030 ha |
|                                                                                  | 0.08% of total land area | 0.34% of total land area | 0.03% of total land area | 0.01% of total land area | 0.20% of total land area |
|                                                                                  | 5.25% of irrigated land area | 28.26% of irrigated land area | 44.38% of irrigated land area | 3.56% of irrigated land area | 18.79% of irrigated land area |

### Notes
- * Lease/Permit area figures have had any overlapping/duplicate areas removed.
- Land Use - State of Queensland (Department of Science, Information Technology, Innovation and the Arts) 2012.
- Resources Leases, Licenses and Permits etc. - State of Queensland (Department of Natural Resources and Mines) 2012 (Downloaded 27/9/2012).
12.4 EFFECTS OF POTENTIAL LOSS OF IRRIGATION ACTIVITY DUE TO MINING

Whilst not all the mining activity over the 94% of the irrigated lands will result in underground mining, the threat of mining reduces the ability of landholders to obtain funds for investment in land improvement.

Additionally the cotton industry requires a critical mass of production to maintain facilities. Depending on the extent of reduction, loss of cotton growing area or production due to mine subsidence could put the entire cotton industry in Emerald in jeopardy.

12.5 EFFECTS OF MINE SUBSIDENCE ON WATER SUPPLY INFRASTRUCTURE

The irrigation water for cotton growing in the Emerald Area is supplied via gravity fed channels (GHD, 2001). Figure 12.1 shows the main distribution channels. Any creation of undulations in the supply channels will result in significant risk of overtopping and/or humps across the supply system. These changes in grade will significantly disrupt the regional irrigation water supply. That is, the Sunwater system will be at risk.

Expensive large scale lining or concreting of the channels will be needed.

The main cotton growing area is to the north/northwest of Emerald. It is supplied via the Selma Channel. Some 42.8 km of this channel is constructed of unlined earth, while 1.7 km is concrete lined. There is some 2.1 km of pipe (GHD, 2001). All three systems will be susceptible to mine subsidence damage.

The unlined earth structure is likely to crack and leak severely. In subsidence areas overtopping may occur.

The concrete lining can fail if there is sufficient differential pressure on it. Similarly the pipeline joins can separate causing pipe failure.

Virtually all the irrigated cotton growers have sophisticated earth-lined distribution channels for conveying water to individual fields. Subsidence is likely to cause problems with grades, leakage and overtopping. These risks are illustrated in the figures in section 8 of the current report.

Floods in the Emerald Areas since 2009 have demonstrated the vital importance of levees along the Nogoa River and its tributaries. Mine subsidence would put the integrity of the levees at risk. Even levees ‘out of town’ can be overtopped and the water can then enter the Emerald Urban Area.
Figure 12.1. Channels and pipelines of the Emerald Irrigation Area (Copied from GHD, 2001).
12.7 Mine subsidence impacts on agriculture in the Emerald Area

Hinchcliffe (2003) examined dryland wheat growth on
- un-subsided land,
- subsided pillar land,
- subsided panel land and
- subsided middle panel land

Soon after mining operations commenced at two mines near Emerald.

The coal seams were 2 to 3.5m thick and subsidence varied from 1.8 to 1.9m in the middle of the panel to 0.4 to 0.5m in panel areas.

The study involved dryland soybean and low yielding dryland wheat crops over 2 years. One year had slightly less than average rainfall and the other had very dry conditions.

Wheat yields at one site (Crinum) were statistically higher from the subsided area than from the un-subsided area. Wheat yields at Kestrel Mine were statistically the same irrespective of subsidence.

Note that dryland wheat crop requirements are completely different to irrigated cotton. Irrigated cotton is largely reliant on external water. Any effect on its supply (e.g. subsidence of irrigation systems or within fields) or availability in the soil (e.g. compaction increasing bulk density and reducing water holding capacity) will reduce yield.

Importantly, the Hinchcliffe (2003) study also revealed that the subsidence area had wetter profiles at the Crinum site in year 1. The greater accumulation of water via runoff of summer rain in the subsidence areas is likely to increase wheat crop productivity in a subsequent dry winter.

The key aim of irrigation is to reduce crop water stress via reducing crop water deficit. Rapid surface drainage is essential in order to maximize cotton yield (Hodgson and Chan, 1983). Therefore, creation of closed depressions within an irrigation field is likely to result in prolonged waterlogging, and this will reduce cotton yield as well as make farming operations extremely difficult if not impossible.

Yield of winter crops (which largely rely on soil water stored over the summer), may be higher in the subsidence areas because runoff into the depression and prolonged inundation during the previous summer would assist in maximizing soil water storage. Additionally the depressed growth of cotton on the waterlogged soils in the previous summer would mean that less of the water would have been transpired. So more soil water would be available for the subsequent wheat crop.

It is therefore likely under these conditions that winter-grown crops such as wheat would be more productive in the subsidence areas than on un-subsided ground. Conversely, in wet winters, the wheat growing in the closed depressions would become waterlogged and highest yield would be obtained from un-subsided areas (Melhuish, et al 1991). The Hinchcliffe (2003) studies were only for two years. It is understood that, because of mining, the area studied by Hinchcliffe (2003) is no longer suitable for normal farming operations.

Darmody et al (1988) makes the important observation that subsidence on very flat land is likely to be visually more conspicuous than on hilly lands. On flat lands the subsidence is likely to create hollows where excess water accumulates due to lack of surface drainage. This would be especially damaging to laser graded lands that were flood or furrow irrigated. Darmody(1995)
states that wet areas within subsidence creates problems including limited periods where the area is suitable for cultivation, low seedling establishment percentage, nutrient deficiency, poor root development, and increase disease incidence. All these features can reduce irrigated cotton yield.

An additional issue is that growth variation within individual field makes management difficult. During early growth the more vigorous cotton plants are more responsive to fertilisation and irrigation. During mid-season, the subsidence lands are likely to still have sufficient water, but the adjacent plants require irrigation to maximise yield. This will result in overwatering of subsidence lands. Near harvest time, the greater soil water content in the subsidence areas prolongs the season, creating risk of frost damage and delaying field access.

The table below shows the combined effects of mine subsidence on maize yield for a range of wet and dry years.

Table 12.1. Effect of degree of subsidence on percentage change in maize yield (from Darmody, et al 1989, discussed in Hinchcliffe (2003)).

<table>
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<tr>
<th></th>
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</tr>
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<tbody>
<tr>
<td>Slight</td>
<td>29.</td>
<td>30.</td>
<td>31.</td>
<td>32.</td>
</tr>
<tr>
<td>Moderate</td>
<td>34.</td>
<td>35.</td>
<td>36.</td>
<td>37.</td>
</tr>
<tr>
<td>Severe</td>
<td>39.</td>
<td>40.</td>
<td>41.</td>
<td>42.</td>
</tr>
</tbody>
</table>

A key conclusion was that yield loss was greatest in the ‘severe’ subsidence class. Large yield losses were associated with wet years. This conclusion is consistent with the concept that subsidence results in closed basins that are likely to remain waterlogged for agronomically significant periods in wet seasons or following irrigation.

Darmody et al (1989) also examined the yield loss weighted for the proportion of the area impacted by subsidence. They found yield loss within longwall mining areas ranged from 7% in a wet year to 2% in a dry year. High extraction retreat mining resulted in less loss of yield, possibly because the subsidence was not as great.

In another report Darmody (1995) used GIS techniques to model impacts of longwall mine subsidence. Subsidence was recorded on 35% of the mined area and maize yield loss ranged from 4 to 10% for individual panels. Areas with severe impact suffered 95% yield loss. It is noted that both maize and cotton are very sensitive to waterlogging.

Hinchcliffe (2003) cited a study with summer growing sunflowers that were sown on ‘pillar’, ‘subsidence’ or ‘un-subsided’ sites. There was little information presented, however the highest yield was from the ‘un-subsided’ sites as figure 12.1 shows. Note that the differences were not statistically significant. Additionally the yields were very low, suggesting that other factors dominated plant performance.
RISKS AND IMPACTS OF COAL MINE SUBSIDENCE ON IRRIGATION AREAS

Frazier, et al, (2010) used remote sensing techniques to detect impacts of coal mining on agriculture. They concluded that their techniques could not find evidence that subsidence impacted on crop performance. Unfortunately, the study did not provide much detail concerning on-ground conditions in the study area. Similarly, Thompson, et al (2011) monitored the effects of longwall mine-induced subsidence on vineyards. They found no obvious viticultural effects. Their results may be due to the presence of slopes which would enable surface drainage despite subsidence. These results, and those of Hinchcliffe (2003), indicate that yield loss on mine subsidence land is not universal. Rather it occurs when a set of conditions are present. These conditions include:

- The land surface is relatively flat
- The soils are clay dominant (especially cracking clays)
- The site is flood or furrow irrigated
- The crop is sensitive to waterlogging
- The crop is grown in summer when warm temperatures will increase soil respiration rate, reducing the time to onset of anoxic conditions

All of the above determinants apply to irrigated cotton growing in the Emerald area.

12.7 POTENTIAL FOR RESTORATION FOLLOWING MINE SUBSIDENCE

The potential for restoration to pre mining productivity has been examined in numerous sites throughout the world. The main recorded limitation seems to be the loss of drainage capacity. The importance of the loss depends on the post mining enterprise. In China permanent ponds have been developed in subsidence areas and then used for fish production.

In Illinois, restoration was successful for crops such as non-irrigated soybean, which could tolerate some waterlogging. However maize yield was significantly reduced (Darmody, et al 1992). Darmody, (2000) provides some guidance on reclamation of mine subsidence lands, but the cost and difficulty are emphasised. Finding sufficient suitable fill would be a major issue in the Emerald Area.

The Commission on Engineering and Technical Systems (CETS), (1991) identified the need for an overall strategy to address the problems created by subsidence. However many of the proposed strategies are extremely expensive, exceeding the value of the mined products. It would be preferable to avoid the problem in the first place.
13. SUMMARY AND CONCLUSION

- Some 94% of irrigated lands in the Central Highlands of Queensland are covered by various mining exploration / mining licenses.
- Based on long term experience throughout the world, subsidence is virtually an inevitable impact of underground mining.
- The extent of subsidence varies with type of mining, with bord and pillar likely to slowly create melon hole type landscapes, while longwall mining creates long closed rectangular basins within a few months of mining.
- In both cases the subsidence area extends beyond the physical boundaries of the mined area.
- The depth of the subsidence varies with mining type and local geology. The maximum subsidence under longwall mines is around 65% of the coal seam thickness. Thus a mining a 2m seam will result in a typical maximum of 1.3m subsidence. The initial bord and pillar working, typically removes 30% of the coal, and results in initial depressions of a few centimetres. Second working to increase coal removal to closer to 50% causes partial collapse of the remaining pillars and the subsidence depth eventually approaches that of longwall mining.
- Subsidence from bord and pillar mining is gradual, so there is a need to continually adjust surface activity to allow for its occurrence.
- Subsidence of even 0.5m is predicted to have catastrophic effects on irrigated cotton growing. The key reason is that the cotton fields are laser graded to 1:1000 to 1:1500 slopes, i.e.0.6 to 0.85m fall over an 850m irrigation run. A 0.5m depression across such an irrigation run would make it inoperable. The field could be regraded, however the long subsidence period under bord and pillar systems means that regrading will need to be repeated a number of times. Additionally, there is the practical difficulty of finding the large quantity of suitable fill required.
- Other subsidence impacts on irrigated cotton soils include waterlogging, compaction and irregular ripening of the crop. Salinisation may also be encouraged. All these impacts reduce cotton yield.
- Infrastructure including irrigation supply channels, flood levees, farm dams, farm buildings, cotton processing facilities, roads and tracks are all under threat from mine subsidence.
- Irrigated cotton is largely on black cracking clays (vertosols). These soils are highly prized for irrigated cotton growing and there are very limited opportunities to re-establish irrigated cotton growing elsewhere.
- Yield loss on mine subsidence land is not universal. Rather it occurs when a set of conditions are present. These conditions include:
  - The land surface is relatively flat
  - The soils are clay dominant, especially with cracking clays
  - The site is flood or furrow irrigated
  - The crop is sensitive to waterlogging
  - The crop is grown in summer when warm temperatures will increase soil respiration rate, reducing the time to onset of anoxic conditions

All of the above determinants apply to irrigated cotton growing in the Emerald area.

Both irrigated cotton growing and mining are legitimate activities that contribute significantly to Australia’s wealth. However there is a fundamental incompatibility in landuse. Co-existence on the same parcel of land is not viable. This makes subsurface mining a major threat to the viability of long established irrigated cotton lands.
14. REFERENCES


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