Prospects of improving flooding tolerance in lowland rice varieties by conventional breeding and genetic engineering

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Flooding is a recurrent phenomenon in several lowland rice-growing areas in India and elsewhere. Even though rice is a reasonably flooding-tolerant crop, the annual loss incurred by farmers due to floods is large. There are excellent traditional rice types with high level flooding tolerance. Combining high level flooding tolerance to high grain yield through conventional breeding has been successful to a limited extent so far but there are enormous opportunities for the same. There are also hopes that flooding tolerance can be genetically engineered in rice using a transgenic approach. We take a look on the prospects for improvement of rice to flooding stress through conventional breeding and through plant genetic engineering.

RICE is the most important food crop in the world consumed by nearly 3 billion people almost daily. Nearly 25% of the world's rice (i.e. 38 million hectares) is cultivated in the rainfed lowland ecosystem. However, the produce from rainfed lowland ecosystem accounts for only 17% of the global rice supply. Figure 1 shows distribution pattern of lowland rice areas in South and South-east Asia. India has the largest area (i.e. 17.2 million hectares) under rainfed lowland amongst the South-east Asian countries[1]. About 75% of the world lowland rice is in the belt across Eastern India, Bangladesh, Myanmar and Thailand.

Submergence due to flash-floods is the key factor limiting yield of lowland rices. Widawsky and O'Toole[2] showed that out of 42 biotic and abiotic stresses which prevail in rainfed lowland rice areas of Eastern India, submergence stress is the third most important limitation to rice production (surpassed by drought and weeds). Flash-floods are highly unpredictable and may occur at any growth stage of the rice crop and the yield loss may be anywhere between less than 10 and 100% depending on factors such as water depth, duration of submergence, temperature, turbidity of water, rate of nitrogen fertilization, light intensity and age of the crop[3]. Gases diffuse 10,000 times slower in water than in air[4]. Hence growth and survival during submergence of rice is affected by partial (hypoxia) or complete loss (anoxia) of O_2. Reduced supply of O_2 and CO_2 as well as reduced C_2H_4 diffusion limit respiratory activities, photosynthesis and have a negative impact on elongation and growth of rice plants.

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Rice plants respond to flooding stress through (a) elongation ability by which varieties in situation of stagnant or deep water flooding (water depth 60–100 cm) avoid complete submergence through elongation of leaf sheath, leaf lamina and internode leading to emergence of the plant above the rising flood water levels, and (b) submergence tolerance by which certain rice varieties survive submergence of 10 days or more particularly in shallow water [water depth up to 40 cm (as per the classification followed in India) up to 50 cm (as per the classification followed at the International Rice Research Institute (IRRI)); water depths mentioned are approximations as it is still a debatable issue] through metabolic adjustments. The latter situation prevails particularly in lowland ecosystems. Is it possible to change the genetic make-up of rice plant by conventional breeding and by genetic engineering to make it more tolerant to flooding stress? We discuss this theme in the present review.

Improvement of submergence tolerance through conventional breeding approach

Rice crop in lowland areas is invariably subjected to flooding stress continuously for varied periods. The traditional rice varieties have evolved suitable mechanism(s) to survive under this stress. Systematic screening of rice germplasm has shown that there are excellent flood-tolerant rice types locally available. Among these are especially the 'FR13A' and 'FR43B' of India, 'Kurkaruppan' of Sri Lanka and 'Goda Heenati' of Indonesia. The comparative performance of 'FR13A',

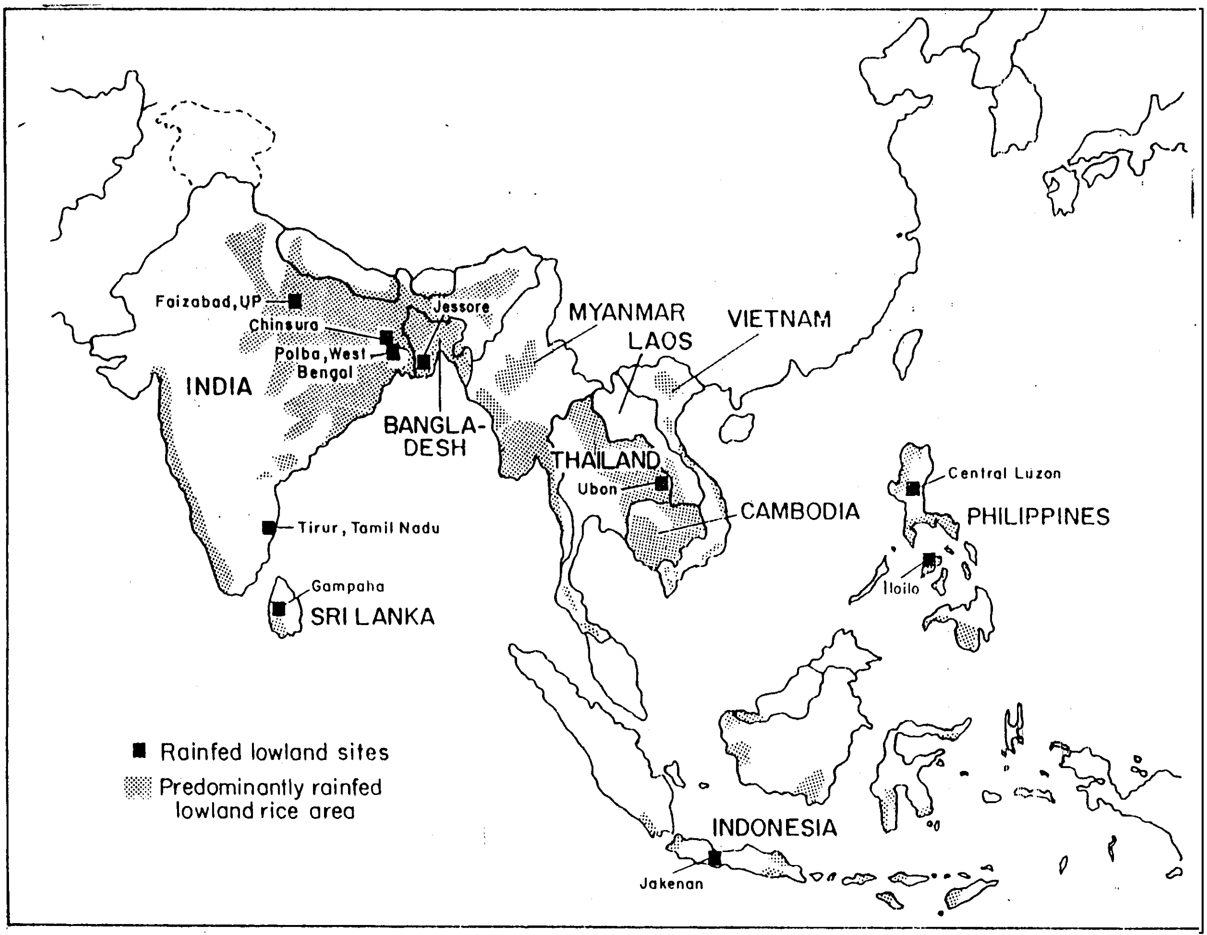

Figure 1. Predominant rainfed lowland rice areas and proposed rainfed lowland key sites in South and South-east Asia (from IRRI 1992 – rainfed lowland rice research consortium).

'FR43B' and several other rice types is shown in a field experiment[5] in Figure 2. Detailed study on such contrasting rice types has indicated that flooding tolerance is controlled by one or a few genes with major effects and additional genes with smaller, modifying effects[6]. However, the traditional lowland rice varieties are lodging-prone because of their tall stature. Further, these varieties are susceptible to diseases and insect pests. Such varieties are unsuitable for large-scale cultivation. It is therefore an attractive research proposition to transfer submergence tolerance from traditional cultivars into more productive modern varieties.

One of us (H.K.M.) took up this challenge in the early eighties and isolated a number of promising breeding lines with good plant type and submergence tolerance such as 'IR 26702-25-3' ('FR13A' source) and 'IR 31406-333-1' ('Kurkaruppan' source)[7]. Subsequent breeding efforts at IRRI led to evolution of tolerant lines with good agronomic traits. The line 'IR 49830-7-2-2' combines high tolerance levels with higher yield potential and resistance to diseases and insect pests and it has been extensively used as a donor parent in the breeding programme. 'Sudhir' is another variety which has been developed from the 'FR13A' × 'Biraj' crosses[8]. This variety has been released by the 'Central Variety Release Committee, Indian Council of Agricultural Research, Government of India' in 1999.

In spite of the above developments, till date no variety has been developed which combines desirable levels of flooding tolerance with grain yield. It is attributed to the fact that 'FR 13A' is a poor combiner for yield and other agronomic traits. Apart from 'FR 13A', 'BKNFR 76106-16-0-1-0' and 'Kurkaruppan' have major dominant gene for submergence tolerance. Flooding tolerant rice 'Goda Heenati' apparently does not have the same submergence tolerance gene. This fact offers hope for pooling diverse genes for submergence tolerance to increase tolerance even above what we have at present. It has been suggested that there are at least three submergence tolerance genes in 'FR13A', 'Kurkaruppan' and 'Goda Heenati'. Further, though 'FR13A' is considered to be an excellent source of submergence tolerance specially at young seedling stage (10 days), 'CN 540 (Suresh)' is found to be more resistant than 'FR13A' at

Figure 2. Comparative performance of FR13A and several other rice types. (Top panel), Submergence treatment was given for 14 days at water depth of 75 cm by placing the pots in submergence tanks; (Middle panel), Comparison of IR 42 and FR13A varieties following desubmergence at young seedling stage. Pots placed behind the Labels represent control plants; (Lower panel), Comparative performance of submerged and control plants of different rice varieties. This experiment was performed employing 50-days-old plants. The submergence treatment lasted for 12 days at 100 cm of water (see Mallik[5] for more details).

an older stage (40 days) and 'FR43B' remains resistant at all growth stages[9]. Therefore, it is proposed that the development of a bridge parent combining both types of resistance (such as 'FR43B') might result in genotypes with better submergence tolerance.

Major attempts have also been made in breeding for improved submergence tolerance through the use of double haploid lines (DHLs), developed using crosses between submergence tolerant and sensitive rice cultivars[10]. The role of DHLs is to screen up several hundred lines within each population for submergence tolerance in representative areas of flash-flooding. Two DHL populations for submergence tolerance have been developed at IRRI using the cross combination of (1) 'IR 49830 × CT 6241' and (2) 'FR13A × IR 42'. These populations were evaluated simultaneously in Thailand and Philippines. In Thailand, a distinct bimodal distribution of lines for survival after submergence was observed supporting the concept of a single gene for submergence tolerance[11]. However, the result from Philippines did not support this theory. Differential responses of DHL populations for submergence tolerance to varying environments signifying G × E interaction, suggest the need for location-specific breeding efforts. The inability of reproducing the result at different locations is a major concern in current research with DHL populations.

Use of DHLs has recently been reported for identification of two RFLP (restriction fragment length polymorphism) markers for submergence tolerance of rice which are mapped to a segment of chromosome 9. This chromosome segment [Sub 1(t)] accounted for 70% of the phenotypic variance in submergence tolerance of this population[12]. It would be rewarding if the Sub 1(t) locus is cloned through map-based cloning technique. Recently, a high-resolution map has been constructed around the Sub 1(t) locus through the use of RFLP and AFLP (amplified fragment length polymorphism) markers. Present attempts are focussed on cloning of tightly-linked AFLP markers for eventual screening of gene libraries[13].

The 'International Conference on Lowland Rice' in 1984 showed that none of the countries in South and South-east Asia had an effective breeding programme for submergence tolerance with the exception of Thailand where two promising tolerant lines 'BKNFR 76106-16-0-1' ('FR13A' source) and 'BKNFR 76109-7' ('FR43B') were developed[14]. Release of short/intermediate height (90–120 cm) high-yielding varieties like 'Jagannath' (OUAT) and 'Pankaj' (IRRI) in India in 1969 and 'Mahasuri' in Malaysia in 1971 was a landmark in lowland rice breeding[15]. The two releases 'Savitri' (Central Rice Research Institute; CRRI) and 'IR42' (IRRI) in the early eighties possessed high yield potential (up to 9 t/ha in 'Savitri') and resistance to diseases and insect pests (in 'IR42') and also adaptability to adverse soils in the latter. However, these varieties lack submergence tolerance to the tune of 'FR13A'. Presently, these are being used as the base material in breeding for submergence tolerance. A significant change in the breeding approach in the nineties is the operation of the 'Shuttle Breeding Programme' in different tracts in South and South-east Asia. The 'Eastern India Programme' started operating in Kharif 1992 and is jointly coordinated by CRRI and IRRI. IRRI supplied seeds of F_2 generation of target crosses for selection under local conditions. Locally-developed elite lines and breeding lines from IRRI including DHLs and somaclonal variants were evaluated in shuttle breeding at a number of cooperating centres in Eastern India. A number of tolerant lines with good agronomic features have been identified such as 'IR 67626-2-2-1' at Chinsurah and 'TCA 95-6', 'IR 67637-14-3-3' and 'IR 67637-11-2-6' at Masodha[16]. The variety 'Sabita' released by one of us (S.M.) is a national check for the semi-deep water ecosystem since 1987 and also a check in 'Shuttle Breeding Programme' since its inception. This variety has been utilized by IRRI in more than 30 crosses and the progenitors from these crosses have been shown to possess a good grain type, wide adaptability and submergence tolerance. As the Cooperator of this programme, S.M. is involved in exchange of F_1 and F_2 seeds amongst different institutions, to make sure that it is a multi-way trafficking of research findings.

The promising tolerant lines of 'Shuttle Breeding Programme' were not included in the shallow water lowland trials for Eastern India of 'All India Co-ordinated Rice Improvement Programme (AICRIP)' for a while which was a matter of concern. However, beginning with Kharif 1999, the materials developed from 'Shuttle Breeding Programme' (such as 'NDR9730004, NDR96007, NDR96006') have been included in the 'National Programme (AVT- shallow water)'. Further, the 1999 workshop of AICRIP (Directorate of Rice Research, Hyderabad) recommended release of the lowland lines 'OR877-ST-4-2' (developed at OUAT from 'IR42/Savitri//IR42') and 'CN1035-61' (developed at Chinsurah from 'Pankaj/IR38699-43-1-2//IR41389-20-1-5') for semi-deep situations for their moderate level of tolerance to submergence and high and stable yields. The line 'CN1035-61' has also been tested through the 'Shuttle Breeding Programme' and considering its good performance during the last two years, it has been reconsidered for inclusion in 'AVT- shallow water'.

Improvement of flooding tolerance in rice through plant genetic engineering approach

Research on rice molecular biology and biotechnology has made great strides during the past 15 years. Rice has emerged as a model cereal crop for research on molecular and genetic studies. Research on this crop has received tremendous support through different funding bodies including the Rockefeller Foundation, USA through its 'Rice Improvement Programme' and from the Japanese Government through its 'Rice Genome Programme'. The salient features of rice genome, rice molecular biology and biotechnology can be seen elsewhere[17]. Tools and techniques for improvement of rice through genetic engineering approach have been perfected to a great extent in several International and National laboratories. Genetic transformation of rice in the early studies was achieved through protoplast-based methods. However, this task has become more routine with the availability of biolistic approach (through the use of microprojectile gun) and more recently, through the *Agrobacterium tumefaciens*-based approach. A number of different regulatory sequences are now available for controlling expression of transgenes in rice and as a result, the transgene can be either constitutively expressed or expressed in response to a specific stimulus (including anaerobic stress; through use of promoters from genes which strongly respond to flooding stress). The bottom line in this discussion is that transgenic rice with specified genes can be produced[18]. This contention is further supported by the fact that transgenic rice plants tolerant/resistant to viruses, insects, fungal pathogens, herbicides, salts and low temperature stresses are a reality now[18].

The question here is how developments in rice molecular biology research can help in raising flooding tolerant rice. Studies have shown that identification/isolation/cloning of genes which are associated with improved flooding stress tolerance appear to be the limiting factors[18]. A great deal of research in this context is focused on carbohydrate metabolism for the obvious reason that a reduced O_2 supply directly hampers normal respiration resulting in decreased levels of ATP synthesis. It has come to light that the pathway of respiration switches over from oxidation to fermentation mode during anaerobiosis. The induction of ethanolic fermentation pathway is considered to be an important component of responses which are elicited in rice (and other plants) against flooding stress[18,19]. A good correlation between anoxia tolerance and rate of ethanolic fermentation is further evidenced through analysis of null mutants of *Zea mays* and *Arabidopsis thaliana* which are unable to produce ethanol and die more rapidly under anaerobic stress than the wild type plants[18,20,21]. The operation of ethanolic fermentation (pyruvate to ethanol) is a relatively simpler trait involving only two enzymes (i.e. pyruvate decarboxylase or PDC and alcohol dehydrogenase or ADH). The availability of cloned *pdc* and *adh* genes (from microbial as well as higher plants) has naturally prompted interest of molecular biologists to employ these for transgenic experiments. Cris Kuhlemeier's groups (University of Berne, Switzerland) has produced transgenic tobacco plants which have a constitutive capacity of ethanolic fermentation by expressing *pdc* gene obtained from obligate anaerobe *Zymomonas mobilis* that had been subcloned to CaMV 35S promoter. This group noted that while over-expression of the bacterial *pdc* caused only a moderate increase in acetaldehyde and ethanol production in the transgenic roots under anoxia compared to wild type roots under the same conditions, the increased ethanolic flux did not enhance anoxia tolerance[22,23]. However, it is too early to make conclusions that increased *pdc* (and also *adh*) has little or no role in submergence tolerance because the following pertinent possibilities are yet to be explored: (a) What happens if different promoters (with varying strengths and not only constitutive but also anoxia-induced) are employed to bring differential levels of *pdc* expression? (b) What happens if concomitant high level *pdc* and *adh* expression is brought in the same cell? (c) What happens if rice rather than tobacco is employed as the host system for such work because tobacco and rice may differ in their response to flooding? A group at CSIRO, Australia is currently working on genetically altering levels of *pdc* and *adh* in rice. One of us (A.G.) is associated with this group for the past 6 years in the programme in which 3 different rice *pdc* genes (*pdc1, pdc2* and *pdc3*) have been cloned and sequenced; *pdc1* cDNA has been subcloned at the 3′ end of three different promoters (CaMV 35S, actin 1 and anoxia-induced 6X ARE promoter which is a synthetic promoter) in both sense and antisense orientations and these plasmid constructs have been introduced into rice to yield a large number of transgenic lines[21,24,25]. One of the above gene constructs (actin 1-*pdc1*, sense) has been employed at IRRI for the production of transgenic rice with enhanced metabolic capacity under anaerobiosis conferring submergence tolerance[26]. In this study, tillers of confirmed T_0 plants showed higher PDC activities and ethanol production compared to untransformed control and consequently ethanol production of tillers of T_0 transgenic plants was positively correlated with survival after submergence. The group at CSIRO has also made considerable progress in altering levels of *adh* gene in transgenic rice plants[27]. However, the assessment of the lines with altered ADH levels with respect to submergence tolerance has not yet been completed[25].

Future work has to be taken up on the following lines: (1) Apart from PDC and ADH, several other enzymes play a role in (a) mobilization of carbon from complex carbohydrate forms (i.e. starch, sucrose etc.) to simpler six-carbon forms which readily enter glycolysis (i.e. glucose); and (b) metabolizing the six-carbon simpler sugars to pyruvate[19,28]. These include glucose phosphate isomerase, phosphofructokinase, aldolase, triose phosphate isomerase, glyceraldehyde phosphate dehydrogenase, enolase, pyruvate kinase and phosphoglycerate kinase. Most of these enzymes show an up-regulation (in terms of enzyme activity as well as transcript levels) in response to anoxia stress[19]. However, till date no attempts directed at making transgenics over-expressing these genes have been reported. There is a need to follow reverse genetics approach to find utility of these genes/proteins. (2) Abiotic stresses (including flooding stress) elicit multiple responses. Therefore, expression of the entire battery of stress-responsive genes would obviously have a greater beneficial effect on stress tolerance than the individual genes. Recent experiments show that by changing the transcription factor genes, it is possible to alter levels of several target genes at the same time[29,30]. For this to be achieved in the context of anoxia stress, understanding of the transcriptional activation of anoxia-induced genes is a prerequisite. (3) Another level in the hierarchy of genetic controls which have a bearing in regulating stress responses is exercised at signal transduction pathways. This is evidenced by the findings of Pardo *et al.*[31] who recently raised salt-tolerant transgenic plants by altering a signal transduction component. The plant stress signalling involves participation of G proteins, cAMP, cGMP, calcium/calmodulin, inositol phospholipids and kinases/phosphatases. Ca^{++} has been found to play an important role in induction of several stress responsive genes (including flooding stress). The strategies for altering signalling pathway in flooding stress response are yet to be discussed and tested.

Future outlook

The conventional breeding approach has made reasonably good progress in producing flooding tolerant rice. However, there are several avenues for future research in this endeavour. The range of flooding tolerance donors from divergent sources must be extended in the future breeding programmes. Screening methods for flooding tolerance need re-addressal. The screening method presently followed using 21-days-old seedling submerged for 14 days appears to be drastic and thereby promising breeding lines with even adequate level of tolerance get eliminated. Screening for submergence tolerance at adult stage is equally important. Besides submergence tests, the breeding material must be subjected to other on-farm biotic and abiotic stress factors. The material thus developed might possess desirable traits needed for rainfed lowland areas including high degree of submergence tolerance. In on-farm evaluation test, breeding lines should be exposed to natural floods. Selection efficiency in breeding population could be enhanced by use of molecular markers. Identification of the RFLP/AFLP markers flanking Sub (1)t locus is an important step in this direction. Yield and submergence tolerance are generally negatively associated. If this association is linkage, attempts need to be made to break this linkage by repeated back-crossing to produce lines that combine high yields and submergence tolerance.

More basic research on regulation of flooding response in terms of transcriptional activation of stress-responsive genes and signal transduction mechanisms is the need of the hour to make transgenic rice for improved flooding tolerance. There is also a need to identify, isolate and clone genes which are induced in response to flooding stress and to test the functional relevance of such genes in rice flooding tolerance response through the reverse genetics approach. The construction of suitable gene libraries, differential display, subtractive hybridization and other related techniques would be helpful to obtain this goal. The recently initiated 'Rice Genome Project (RGP)' aims to provide nucleotide sequence of the complete rice genome. The information from this project would hopefully provide function and location of additional genes important for flooding tolerance.

Finally, it is argued that IR 36, the most adapted stable variety across countries in irrigated ecosystem has diverse genes from 18 parents originating from 11 countries. Why can the same not be achieved for the lowland ecosystems? Effective integration of conventional breeding and biotechnological efforts might lead to a variety like IR 36 for the diverse, unpredictable and flood-prone environments of rainfed lowland ecosystems. Indian laboratories have the requisite support in terms of germplasm availability to carry out this programme. However, it is important to supplement this through additional support for exploiting this germplasm for desired goals. It must be borne in mind that such programmes have lucrative ends in sight and therefore, one has to move against time to make a dent in international markets for the superior products (i.e. seeds of the elite types). Adaptation to flooding in semi-deep water, deep-water and floating rice will be reinforced if they have seedling submergence tolerance in addition to elongation ability.

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Oil and gas exploration in deep water: An overview

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There has been increasing interest in deep water oil and gas exploration. What is deep water exploration and why is the international industry so keen on it? What have been the implications to the oilfield service sector in view of increasing deep water oil and gas exploration activities in many parts of the world? This article reviews recent developments in deep water exploration, with emphasis on the Indian scenario. ONGC has already drilled two wells and there are a number of large structures in deep water in excess of 400 m water depth. It is likely that in the coming years, deep water drilling in the Indian offshore would result in discovery of oil and gas.

WITH continuing advances in exploration and production technologies, the minimum water depth from which hydrocarbons were produced rapidly increased from 60 m in 1960 to nearly 2000 m as of today. Now, the depth at which a deep water field starts is being redefined.

As seen in Figure 1 the oil industry has made rapid progress in pushing the depth of sub-sea production. Within the next five years it is expected to exceed 2500 m (ref. 1). Various organizations have evolved their own definition of deep water ranging up to 500 m and even beyond. For example, in offshore Brazil, Petrobras classifies 'deep water' as 400–1000 m and beyond 1000 m as 'ultra deep'. In the North Sea, 200 m seems to have become the techno-economic limit for fixed platforms; only 3 fields, Draugen (270 m), Gulfaks (217 m) and Troll (330 m) all in the Norwegian sector, use fixed platforms in waters beyond this depth. The Troll A platform is the largest structure ever moved by man.

Why explore in deep water?

As oil from shallow waters is increasingly depleted, deep water reserves are becoming important to oil companies and more so to individual nations. Of the 700 sedimentary basins around the world, 240 are deep water offshore zones, and exploration has begun in half of them[2]. Therefore, there is considerable scope for the discovery of giant fields, an event that has become a rarity in onshore and shelfal offshore areas.

A number of factors contribute to the increase in global deep water activity. (i) Depletion of shallow water reserves, in some regions deep water is the only option. (ii) Greater potential for large finds compared with shallow waters; for example, in India, there has been disappointing potential in the east coast shelf and there is optimism that the deep waters may be more prospective. (iii) Future growth in hydrocarbon demand. (iv) Improved technology and management practices which have reduced development costs. (v) Host governments have evolved favourable fiscal policies towards deep water exploration.

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Oil and gas review – Impact on future deep water developments

Future deep water developments are being reviewed in view of a sharp drop last year in the international oil prices though, of late, there has been a significant recovery. The relevant aspects of the industry are highlighted below:

- Likely slow recovery of oil prices over the next 3 to 4 years as the oil supply decreases and demand increases. This is based on an assumption of economic recovery in various Asian countries in the year 2000 and beyond.
- Despite relatively lower prices in the near term, deep water exploration and development initiatives are generally expected to be sustained worldwide, with offshore West Africa emerging as a major future source of oil production. Technology and resource availability can sustain large increments in oil production capability at prices ranging between $18 and $22 per barrel. The current price environment will, however, slow the pace of development in some highly prospective areas, including especially the Caspian Basin region[3].

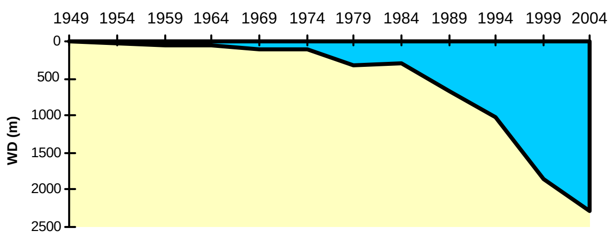

Figure 1. Offshore fields – Maximum depth by year on-stream.

- Economic development in Asia is crucial to long-term growth in oil markets. The projected evolution of oil demand will strengthen economic ties between the Middle East and Asian markets.
- Though Oil Producing and Exporting Countries' (OPEC's) share of world oil supply is projected to increase significantly over the next two decades, competitive forces are expected to remain strong enough to forestall efforts to escalate real oil prices significantly. These competitive forces operate within OPEC, between OPEC and non-OPEC sources of supply, and between oil and other sources of energy (particularly natural gas).

The emerging deep water market

It is estimated that worldwide, in the next 2–3 years, no less than 50 deep water fields would be developed. Review of currently proposed offshore field developments shows that some 44% of these reserves are in depths greater than 300 m. In the Gulf of Mexico and Brazil however, deep water accounts for 90% of oil and gas reserves being considered for development. Offshore Brazil, Petrobras expects to boost its current 1 million b/d production to 1.5 million. Of this, 60% will come from water depths greater than 400 m.

At the end of 1996 production from all deep water fields (>300 m) was about 1 million b/d worldwide. Exxon has projected that this would triple to 3 million b/d by the year 2000, accounting for 10% of offshore production.

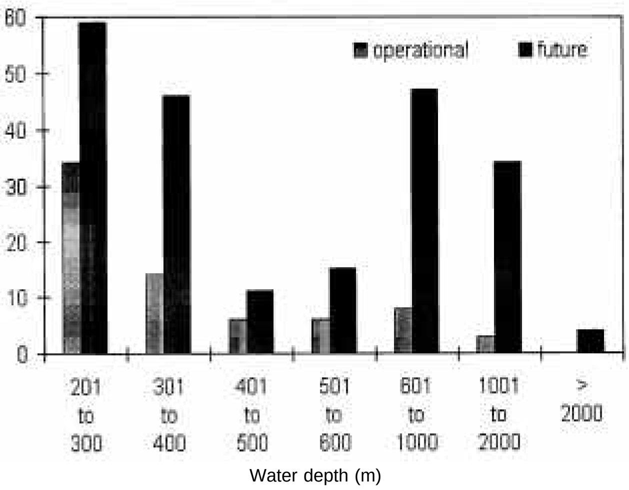

Figure 2. Existing and future schemes against water depth.

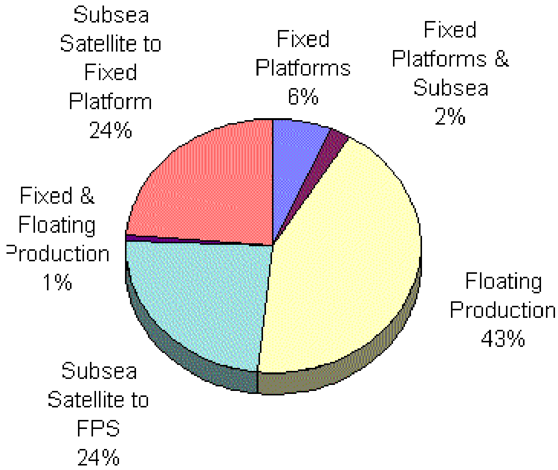

Figure 3. Pie diagram showing various options for development schemes.

Most of the 95 planned field developments are predominantly oilfields (~87) including a number of large ones with daily production rates in excess of 100,000 b/d. However, about 50% are small, and are likely to produce less than 20,000 b/d.

Development schemes for 139 deep water discoveries (out of 216 future deep water fields) show that floating production systems (FPS) are involved in 68%. The other largest category is that of sub-sea satellites tied back to fixed platforms.

Beyond 600 m there are no instances of fixed platforms; however, it is common for sub-sea satellites to be tied back up the slope to platforms in shallower waters. Figure 2 shows the existing and future schemes against water depth with about 100 projects in deep and ultradeep waters (> 300 m, L&T internal report).

Figure 3 shows various options considered for the development schemes and indicates that floating production facility is the most preferred option (L&T internal report).

The Indian scenario

In the 1970s and 1980s, India focused on traditional onshore oil exploration and the reserve accretion was 18 to 30 million tonnes a year. A move to offshore exploration resulted in the discovery of the Bombay High field and reserve accretion yielded a ten-fold increase. Will the shift from shallow to deep water lead to similar boost in India's reserves?

The Bombay High field in shallow waters off the western coast continues to provide the bulk of India's oil production. India's oil production has slowed to below 30 million tonnes a year while annual demand, running at more than 60 mmt, has been rising at about 8%. Because of the stagnating production, the Government has begun to de-regulate the oil industry by inviting participation from both Indian and international companies. There is a clear need for exploring deep water potential off the country's eastern and western coasts. In recent years, ONGC has been extensively acquiring seismic data for this purpose.

ONGC estimates that an investment of at least $10 billion is required for deep water exploration in Indian deep waters ranging in depth from 200 to 600 m. Between 20 and 35% of hydrocarbon potential in India could be found in deep waters beyond 200 m. Based on the Directorate General of Hydrocarbon (DGH) data, which are not very exhaustive at the moment, the Government's estimates of deep water reserves range from 5 to 9 billion tonnes of oil and oil equivalent gas.

Based on the interpretation of seismic data, ONGC has already identified prospective western and eastern offshore areas and has selected four locations for drilling, covering about 1.4 million m^2 in the Arabian Sea and Bay of Bengal. ONGC has upgraded one of its drill ships, *Sagar Vijay* at Cochin shipyard for deep water drilling.

Drilling in the first two locations in Cauvery and KG offshore basins has proved to be disappointing as no oil and gas was found. ONGC now has invited leading deep water firms along with public sector firms like GAIL and IOC for joint ventures to bring in technology, financing and sharing of risk. The Gas Authority of India Ltd (GAIL) has expressed interest in this project, particularly in areas like the Andaman Islands where large gas reserves could exist.

The new exploration policy (NELP) announced in 1999 has thrown open a large number of onshore and offshore blocks. The deep water acreage has been kept separate with a reduced royalty schedule for deep water production. The policy envisions a level playing ground for national and global firms. It is no longer mandatory to offer a 30% ownership to national oil firms in joint ventures. However, there is concern that due to a low oil price environment and massive restructuring of the international energy industry, the interest in NELP acreage may be lukewarm. Most of the large players have evinced more interest in India's deep water acreage.

The Government has also initiated steps to find new oil and gas sources; under NELP, an area of 1.4 mm km^2 in water depth of 200–2000 m has been marked out for hydrocarbons. Seismic data in deep water areas along both the coasts have been acquired through a collaborative effort between DGH and geophysical service companies.

A number of oil companies have purchased seismic data and are looking closely at deep water prospects. $1.8 billion has been committed by ONGC for the next 5 years for its programme. Active cooperation is being sought from Petrobras as the Brazilians have established successful and cost-effective programmes in deep water oil and gas production.

Summary

Deep water oil and gas developments world over are growing strongly with major activities underway in North America, Brazil and Europe. Industry surveys suggest that 95 schemes are under various phases of development in water depths greater that 300 m with combined reserves of about 2.3 billion tonnes oil equivalent. It is likely that by end of the year 2002, 134 fields are likely to come onstream. These developments will require a capital expenditure of about $71 billion over the period, rising from some $10.7 billion in 1998, to nearly $19 billion in 2002. Small finds may provide an opportunity for small independent oil companies to enter deep water development through accessing proprietary technology from contractors for viable development schemes. Many service companies have developed technological expertise for deep water production. The current trend is towards larger all-in-one capabilities which will encompass design, engineering, construction and structure emplacement into one organization.

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